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RECENT STUDIES OF THE UPPER CRETACEOUS OF TENNESSEE[1]

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After an interruption of two years, due to the recent war, the Tennessee Geological Survey has taken up again the study of the Upper Cretaceous series of West Tennessee, an investigation inaugurated in 1915 under the late Dr. A. H. Purdue. The field studies, collections, and surveys necessary for this investigation are now more than three-fourths complete, and it is the purpose of this short paper to give an abstract of the general areal and stratigraphic geology of the region, to touch lightly on the large well-preserved Ripley fauna discovered in the southern part of the state in 1915, and to announce the discovery in 1919 of a large and important Ripley flora in the northern part of the state.

HISTORICAL SKETCH

The first adequate map and separation of the Upper Cretaceous series of Tennessee into formational units was published by Safford[2] in 1869. Troost and others had previously written a little of the Cretaceous of this state but had not definitely described the formations. Safford's work was based on faunal and lithologic studies

[1] Published by the permission of Wilbur A. Nelson, State Geologist of Tennessee.

[2] J. M. Safford, *Geology of Tennessee*, Nashville, 1869, map and pp. 410–21.

and has been little changed even to the present day. In 1906 Glenn[1] published a map and gave a good, serviceable, and important account of the Upper Cretaceous of Tennessee along with his report on the geology and water resources of Tennessee and Kentucky west of the Tennessee River and of an adjacent area in Illinois. Nelson gave a short discussion of the Upper Cretaceous in connection with his studies of the clay deposits of West Tennessee[2] in 1911. The occurrence of the Tuscaloosa formation in Tennessee was shown by the work of Miser[3] on the Waynesboro Quadrangle in 1913. The McNairy sand member of the Ripley was differentiated by Stephenson[4] in 1914. In this same publication the Tennessee Upper Cretaceous deposits were correlated with beds of the same age in eastern United States. In 1916 Berry[5] published an account of about twenty-four species of fossil plants collected from the Ripley and Eutaw of McNairy and Hardin counties. In 1916 and 1917 the writer[6] published several short papers on the discovery of and some observations on a large Ripley fauna of McNairy County and a single article on the occurrence of the Tuscaloosa formation as far north as Kentucky. In 1919 Schroeder[7] gave a very brief outline of the Cretaceous in connection with his report on the Ball Clays of West Tennessee. In the latter part of 1919 Berry[8] published a very comprehensive discussion of the Upper Cretaceous Geology of Tennessee in his monograph on the *Upper Cretaceous Floras of the Eastern Gulf Region.*

During 1915 and 1916 the writer mapped in detail the areal distribution of the Upper Cretaceous formations in McNairy, Decatur, and Chester counties, and in 1919 this work was carried

[1] L. C. Glenn, *U.S.G.S. Water Supply Paper No. 164* (1906).

[2] Wilbur A. Nelson, *Tennessee Geological Survey Bull. No. 5*, Nashville, 1911.

[3] H. D. Miser, *Resources of Tennessee*, Nashville, Vol. IV, No. 3 (1913), p. 107.

[4] L. W. Stephenson, *U.S.G.S. Prof. Paper 81* (1914).

[5] E. W. Berry, *Torr. Bot. Club Bull. 43*, pp. 283–304, Pl. 16 (1916).

[6] Bruce Wade, *Proc. Acad. Nat. Sci.* (Phila., 1916), pp. 455–71, Pls. XXIII, XXIV; *Am. Jour. Sci.*, Vol. XLIII (1917), p. 293, Figs. 1, 2; *Proc. Acad. Nat. Sci.* (Phila., 1917), pp. 280–304, Pls. XVII, XVIII, XIX; *Johns Hopkins Univ. Cir.* (March, 1917), pp. 73–106.

[7] Rolf A. Schroeder, *Resources of Tennessee*, Vol. IX, No. 2 (1919).

[8] E. W. Berry, *U.S.G.S. Prof. Paper 112* (1919).

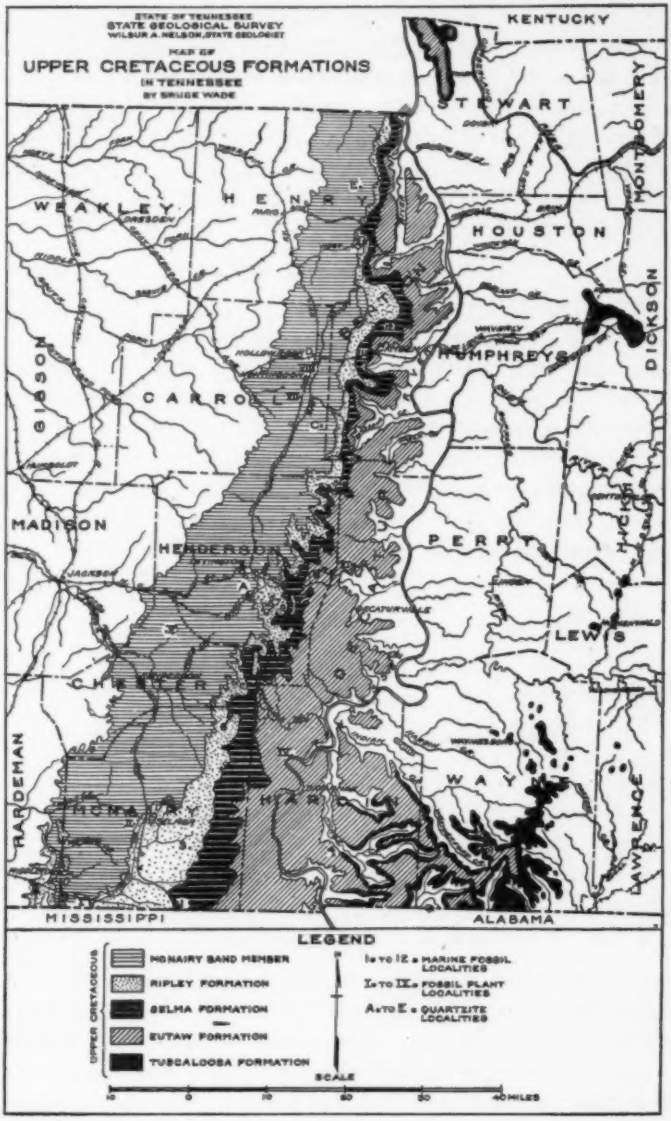

STATE OF TENNESSEE
STATE GEOLOGICAL SURVEY
WILBUR A. NELSON, STATE GEOLOGIST
MAP OF
UPPER CRETACEOUS FORMATIONS
IN TENNESSEE
BY SAVAGE WADE
KENTUCKY
STEWART
MONTGOMERY
WEAKLEY
HENRY
HOUSTON
DICKSON
HUMPHREYS
GIBSON
CARROLL
MADISON
HENDERSON
PERRY
HICKMAN
LEWIS
CHESTER
DECATUR
WAYNE
HARDEMAN
HARDIN
LAWRENCE
MISSISSIPPI
ALABAMA
LEGEND
UPPER CRETACEOUS
MCNAIRY SAND MEMBER
RIPLEY FORMATION
SELMA FORMATION
EUTAW FORMATION
TUSCALOOSA FORMATION
I. TO IE. = MARINE FOSSIL LOCALITIES
I. TO IX. = FOSSIL PLANT LOCALITIES
A. TO E. = QUARTZITE LOCALITIES
SCALE
40 MILES

FIG. 1

northward, where it was completed in Henderson and Carroll counties and in a portion of Henry County. In 1920 or the immediate future the Tennessee Geological Survey plans to complete Henry, Benton, and Hardin counties and map the outliers of Cretaceous gravels on the uplands of Stewart, Houston, Humphreys, and Dickson counties. With the field work of all these counties completed information will be in hand for a complete report on the Upper Cretaceous of Tennessee.

GENERAL GEOLOGICAL RELATIONS

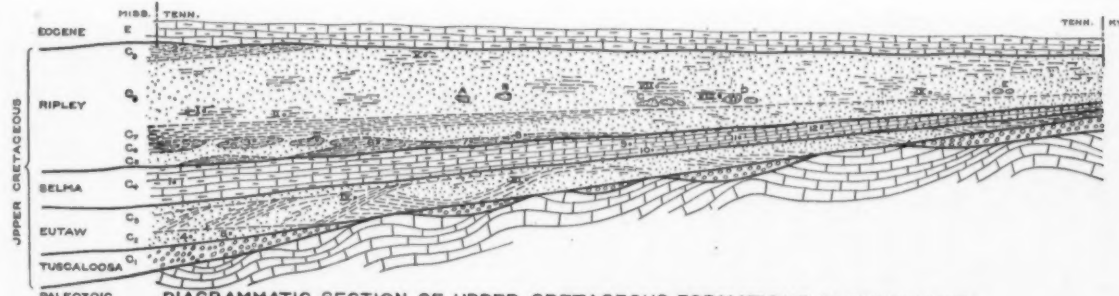
The Upper Cretaceous deposits of Tennessee outcrop in a wedge-shaped area which crosses the state in a nearly north and south direction, and lies largely west of the Tennessee River in the west-central part of the state (Fig. 1). This area is about sixty-seven miles wide along the southern boundary of the state, but narrows to the northward until at the Kentucky line it is only about fifteen miles in width. Along the southern border in Wayne, Hardin, McNairy, and Hardman counties these deposits have been segregated into the following lithologic units:

Ripley formation { Owl Creek horizon or member; McNairy sand member; Ferruginous clay horizon or member; Coon Creek horizon or member }
Selma chalk or formation
Eutaw formation { Coffee sand and clay member; Tombigbee sand member }
Tuscaloosa formation

In the northern part of the state these sediments diminish very greatly in thickness. The four major formational divisions may be recognized but the members or subformations lose their identity (Fig. 2).

THE TUSCALOOSA FORMATION

The Tuscaloosa formation is the basal member of the Upper Cretaceous series in the eastern gulf region of the Mississippi embayment. In western Alabama and eastern Mississippi this formation consists of irregularly bedded sands, clays, and gravels having an estimated total thickness of 1,000 feet. In *Professional*



DIAGRAMMATIC SECTION OF UPPER CRETACEOUS FORMATIONS IN TENNESSEE
FROM NORTH TO SOUTH

FIG. 2

LEGEND

E_1 Eocene, Porters Creek clay, "soapstone"
C_9 Ripley, Owl Creek horizon, fossiliferous sandy marl
C_8 Ripley, McNairy sand member, sands, clays
C_7 Ripley, ferruginous clays of McNairy County
C_6 Ripley, Coon Creek horizon, fossiliferous sandy marl
C_5 Ripley, unfossiliferous sands and clays
C_4 Selma, chalky clays varying to micaceous sandy clays
C_3 Eutaw, Coffee sands and black clays
C_2 Eutaw, Tombigbee sand member with few fossils
C_1 Tuscaloosa, gravels
P_1 Paleozoic limestones, cherts, and shales

MARINE FOSSIL LOCALITIES

1 Blue Cut on M. & O. R.R. at Tenn.-Miss. line
2 Trimms Mill, 3 miles east of Middleton
3 Sand Hill, 11 miles southeast of Selmer
4 Florence Road, 5 miles east of Nixon
5 Bear Creek, 2 miles southwest of Victory
6 Coon Creek, 3½ miles south of Enville
7 Shady Hill, 10 miles southeast of Lexington
8 Perryville Road, 7 miles east of Lexington
9 Cub Creek, 1 mile south of Poplar Springs
10 Yellow Spring Road, 5 miles south of Holladay
11 N. C. & St. L. R.R. Cut, 2½ miles west of Camden
12 Dickerson Place, 4 miles north of Camden

FOSSIL PLANT LOCALITIES

I Big Cut, 1½ miles west of Cypress
II New Bethel Road, 2½ miles southwest of Selmer
III John Boyd Place, 5 miles northeast of Selmer
IV Coffee Bluff, 4 miles north of Savannah
V Jacks Creek Road, 4 miles south of Mifflin
VI Perryville Road, 1 mile north of Beacon
VII Huntington Road, 1½ miles southwest of Buena Vista
VIII Cooper clay pit, 1½ miles south of Hollow Rock
IX Perry Place, 10 miles east of Paris

QUARTZITE LOCALITIES

A Saints Chapel, 6 miles south of Lexington
B N. C. & St. L. R.R., 1 mile west of Lexington
C Big Rocks, 4 miles northeast of Westport
D Hollow Rock, ½ mile west of Hollow Rock Junction
E Elkhorn and Dulac Road, 4 miles north of Elkhorn

Paper 81 of the U.S. Geological Survey L. W. Stephenson has readjusted the nomenclature of the Upper Cretaceous in this region and has defined the Tuscaloosa with reference to the other formations of this series.

Toward the north the Tuscaloosa deposits become much thinner and are made up almost entirely of conglomerates which contain little sand and clay. Professor E. W. Berry[1] has made a study of this series and has found evidence in the fossil plants that the clays, in the basal part of the formation in the region of maximum thickness, are more ancient than plant-bearing clays that occur in the conglomerates about Iuka in northeastern Mississippi where the formation becomes much thinner. He shows that an Upper Cretaceous estuary existed for a long time in western Alabama before it transgressed into the northern part of Mississippi and Alabama.

Until recently the Tuscaloosa formation was thought to thin out entirely in the vicinity of the Tennessee-Alabama line. In 1913 H. D. Miser mapped the areal geology of the Waynesboro quadrangle of Tennessee and found that the Tuscaloosa was one hundred and fifty feet[2] thick and extended over a large part of Wayne County. Subsequent work by the Tennessee Geological Survey showed that remnants of the Tuscaloosa gravel occur in place of the highland rim of Tennessee as far north as northern Lewis County.[3] Farther north, during the summer of 1916, the writer encountered undescribed occurrences of the Tuscaloosa formation which show that the sediments of this transgressive phase of the Upper Cretaceous exist in a chain of local outlying areas across the state of Tennessee and as far north as the ridge west of Canton, Kentucky.[3]

An important link in this chain are the gravels which occur locally along the Nashville, Chattanooga and St. Louis Railroad between McEwen and Tennessee City and capping the higher hills

[1] E. W. Berry, *U.S.G.S. Prof. Paper No. 112* (1919).

[2] H. D. Miser, "Economic Geology of the Waynesboro Quadrangle," *Resources of Tennessee*, Vol. IV, No. 3 (1913), p. 107.

[3] Bruce Wade, "Geology of Perry County and Vicinity," *Resources of Tennessee*, Vol. IV, No. 4 (1914), p. 173; "The Occurrence of the Tuscaloosa Formation as Far North as Kentucky," *Johns Hopkins Univ. Cir.* (March, 1917).

in this part of Dickson County, Tennessee. A cut on the railroad about two miles east of McEwen shows, resting on chert of the St. Louis formation, about thirty feet of very compact, hard, white chert gravel which is very typical of the Tuscaloosa belt across the state. No paleontological evidence has been obtained from the gravels about McEwen to determine the age of these deposits, but after a study of the lithology as well as the geographic and topographic relations, the Tuscaloosa age of the McEwen gravels can hardly be doubted. These gravels are made up of well-rounded water-worn pebbles, most of which are one inch or less in diameter, although many are larger, often ranging up to cobbles six inches in diameter. Many individuals approach a sphere in outline, and in this respect they differ from the river gravels which are common in terraces along the western Tennessee Valley. In the river gravels of this region the individuals are often flat, elongated, and subangular. Small discoidal quartzite pebbles are often conspicuous in the terrace conglomerates. The Tuscaloosa conglomerates consist for the most part of pebbles and bowlders derived from the Lower Carboniferous cherts which are common in this part of the Mississippi basin. Water-worn sandstone and iron-oxide pebbles have not been observed in the Tuscaloosa. This is another feature which serves to distinguish the Upper Cretaceous gravels from the more recent terrace gravels in this part of the embayment region, even though the latter may rest directly on the former, as is frequently the case in the western Tennessee Valley.

South of McEwen, as stated above, the isolated Tuscaloosa gravel areas may be traced along the highland rim across Lewis County into Wayne and Hardin counties and farther into Mississippi and Alabama, where they are overlain by marine Eutaw deposits, and consequently paleontologic evidence may be obtained.

The Tuscaloosa extends also north of McEwen. About three miles west of Canton in Trigg County, Kentucky, at a point just east of where the Fulton and Nashville Highway crosses the divide between the Tennessee and Cumberland rivers, is an exposure of Upper Cretaceous which has already been reported. This exposure occurs in the top of the divide, which is probably more than

three hundred feet above the waters of the Tennessee and Cumberland rivers. This divide is a northern extension of the western Highland Rim of Tennessee, and it is probable that further study of the plateau between the Canton and McEwen localities will reveal isolated occurrences of Tuscaloosa that form an almost unbroken chain of the remnants of this formation from Kentucky across Tennessee into Mississippi and Alabama.

A study of a map[1] of the Upper Cretaceous belt of the eastern gulf region shows that the Tennessee River flows from the east into the Cretaceous in northwestern Alabama and then takes a northerly course just east of the Cretaceous across Tennessee and Kentucky. The geological map shows that the wide Tuscaloosa belt in western Alabama and eastern Mississippi disappears entirely just north of where the Tennessee River flows into the belt, and in the same part of the state the Eutaw belt becomes abruptly narrow and disappears long before it reaches the northern limit of Tennessee. It has been previously shown that the Tuscaloosa formation, though probably not as thick and as widespread as in western Alabama and eastern Mississippi, was at one time an important formation and covered large areas in Tennessee and Kentucky, and that the Eutaw formation extended farther east and north of the areas mapped. The erosion of the western Tennessee Valley has almost entirely removed the Tuscaloosa deposits toward the north, and has likewise removed a large portion of the Eutaw deposits but to a less extent than in the case of Tuscaloosa.

THE EUTAW FORMATION

In the southern part of the state the Eutaw formation is divided into two members: the *Tombigbee sand* and the *Coffee sand*. The former is made up largely of red ferruginous sands that cap the hills of eastern Hardin County and western Wayne County. This member contains a small marine fauna near Burnsville, Mississippi, and fossils from the same horizon perhaps have been collected in Tennessee in Hardin County at a locality about five

[1] L. W. Stephenson, "Cretaceous Deposits of the Eastern Gulf Region," *U.S.G.S. Prof. Paper 81* (1914), map; also E. W. Berry, "Upper Cretaceous Floras of the Eastern Gulf Region," *U.S.G.S. Prof. Paper 112* (1919), map.

miles east of Nixon on the Florence Road and a single species from near the top of the ridge at the head of Bear Creek in Wayne County. Both of these localities are given on the sketch map (Fig. 1). This member is nowhere in Tennessee very sharply demarked from the overlying Coffee member and probably does not extend northward any farther than the northern part of Hardin County.

The *Coffee sand member* of the Eutaw was first recognized and described by Safford and has been discussed by subsequent writers. It is more than two hundred feet in thickness and is typically exposed on the Tennessee River at Coffee Bluff four miles north of Savannah in Hardin County. It is largely a series of stratified and cross-bedded sands and clays. The sands are usually fine and of various colors, often containing an abundance of scales of mica and in places glauconite and pyrite. The sand frequently is interlaminated with thin layers of clay. Dark or black beds of clay containing very fragmentary leaves and often thick beds of lignitized logs or wood fragments are common. Some of the logs are partly or entirely silicified. Many of the larger logs are perforated by the Cretaceous wood-burrowing pelecypod *Teredo irregularis* Gabb,[1] many of which left thin irregular tubes one inch in diameter in the wood. The clays of the Coffee member are highly carbonaceous and contain an abundance of plant remains. Identifiable leaves from these clays are very rare however. Berry[2] has identified sixteen species from Coffee Bluff and ten species from about the same horizon collected at a locality on the Scotts Hill Road five and one-half miles southwest of Decaturville in Decatur County. A small collection of about seven species was made in 1919 from this same member at a locality one mile north of Beacon, Decatur County. Amber is not uncommon in the beds of wood fragments of this member of the Eutaw. A number of small pieces of amber have been collected at Coffee Bluff and at a locality on the Lexington Road two and one-half miles west of Parsons in Decatur County. One of the specimens from Coffee Bluff contains the wings of a Cretaceous caddis fly, *Dolophilus praemissus*

[1] W. H. Gabb, *Jour. Acad. Nat. Sci.*, Vol. IV, 2d Ser. (Phila., 1860), p. 393, Pl. 68, Fig. 19.

[2] E. W. Berry, *U.S.G.S. Prof. Paper 112* (1919), p. 35.

Cockerell,[1] which Professor Cockerell says is the only known specimen of an American amber insect.

Toward the north the Eutaw formation becomes much thinner until in the vicinity of Dulac in the northern part of Henry County near the Kentucky line this formation is only about twenty feet in thickness. At Riverview, a locality about five miles south of Paducah on the Tennessee River in Kentucky, an exposure of 15 feet of typically laminated Eutaw sands and clays may be observed. In the central part of Decatur County, Tennessee, in the vicinity of Parsons and Decaturville, the basal part of the Eutaw contains irregular lenses of fine chert and quartz gravels sometimes several feet in thickness. Some other vicinities in Tennessee where the Eutaw may be studied are Camden, Holladay, Darden, Scotts Hill, Crumps Landing, Pittsburg Landing, Red Sulphur Springs, etc. The general distribution of the formation is given on the accompanying map.

THE SELMA FORMATION

The name Selma was used in Tennessee as a formational name in 1906 by Glenn,[2] who pointed out that the original term, *Selma chalk*, was applied very aptly in Mississippi and Alabama but was inappropriate in Tennessee. The Selma formation, as represented in the northern gulf embayment regions, consists of fossiliferous chalky clays and argillaceous, micaceous sands laid down during the time when the Upper Cretaceous sea was at its maximum stage of transgression. This stage may be traced across the state of Tennessee by its lithology and fauna, separating the underlying Eutaw sands and the overlying Ripley sands. There are no known unconformities in this Eutaw-Selma-Ripley series, which evidently represents a single cycle of transgression and regression of the Upper Cretaceous sea in Turonian and Senonian time. This cycle took place very slowly and probably extended over a long period of time. The cross-bedded largely non-marine sands and clays of the Eutaw represent the advancing stage of this sea. The Selma chalky sediments represent this sea at its maximum expanse

[1] T. D. A. Cockerell, *Proc. U.S. Nat. Mus.*, Vol. II (1916), p. 99, Fig. 6.

[2] L. C. Glenn, *U.S.G.S. Water Supply Paper 164* (1906), p. 26.

at a stage when no coarse detritus was being washed in. Such a sea was especially favorable for the incoming hundreds of marine organisms which developed in great hordes among various forms, especially of mollusca. Conditions favorable for marine life in the extreme northern part of the embayment were not of long duration. Orogenic changes brought in coarse sediments and this sea began to recede, being filled in with sands which make up the Ripley formation. This recession did not take place suddenly and with uniformity but very gradually with some oscillations and sinuosities of the strand line which brought about the various members of the Ripley formation that are well developed in McNairy County and in the northern part of Mississippi.

The Selma formation is a chalky clay of more than three hundred feet in thickness in the southern part of the state but near the Kentucky line it is less than fifty feet in thickness and is made up of sandy, micaceous clay. This formation is well exposed in the eastern part of McNairy County, giving rise to barren, limy hills known as "bald knobs" or glades that are frequently covered with species of Ostrea, Gryphaea, Exogyra, and Anomia. Toward the north it becomes thinner and loses its chalky nature, yet it may be readily recognized. It may be studied in the vicinity of Chesterfield in Henderson County; about two miles west of Holladay in Benton County; two and one-half miles west of Camden on the N. C. and St. L. R.R. in Benton County; four miles north of Camden on the Big Sandy Road; and about two miles west of Dulac in Henry County. Marine fossils are less abundant in the northern part of the state. In Henry and Benton counties all the exposures of this formation have not yet been examined. Among the collections now at hand for study the most northerly locality at which a collection has been made from this formation is at the Dickinson place four miles north of Camden, Benton County, on the Big Sandy Road. From this locality a fauna of about twelve species has been obtained. Some of the same species with a few additional ones have been collected in the new N. C. and St. L. R.R. cut two and one-half miles west of Camden.

Less than forty species of marine fossils are known from the Selma formation in contrast to more than three hundred and

fifty known from the Ripley formation. This probably does not mean that less than forty species inhabited the Selma stage of the Upper Cretaceous sea in the embayment area, for it is most likely that the widely expanded, quiet, Selma stage of this sea was quite favorable to marine life and that a very large percentage of the Ripley species was inaugurated at that time. It does mean that conditions where so little detritus was being brought in were unfavorable for the preservation of very many Upper Cretaceous species. It may be noted that species of Ostrea, Exogyra, Gryphaea, Anomia, Paranomia, and Pecten are very common in the Selma at many localities. Also it may be noted that the shells of these species are very hard and resistant, being made up of a dense sort of cryptocrystalline shell material which withstood the corrosive and chemical effects of the sea and the attacks of a minute organism, while they were being buried in the very slowly accumulating limy muds. It is true that such species as *Ostrea larva* Lamarck and *Anomia argentia* Morton are thin and fragile, yet they are of a compact shell material and more resistant than such thick shells as a number of species of *Cucullaea*, *Crassatellites*, *Pugnellus*, *Volutomorpha*, etc. Perhaps this point may be brought out by the study of the shell materials and the occurrence of the well-known species *Paranomia scabra* (Morton)[1], which occurs in both the Ripley and the Selma. This bivalve is made up of two distinct shell materials: a thin, hard, compact, resistant outer layer similar to the shell material of certain species of Gryphaea, Ostrea, Exogyra, etc., and a softer inner layer of prismatic calcareous shell material which is similar to the shell material of most of the Ripley univalves and bivalves. In the Selma formation only the thin outer layer of *P. scabra* is found preserved. In the Ripley formation, however, at localities where there are abundant shells of various species unknown in the Selma both the inner and outer layers of *Paranomia scabra* occur perfectly preserved. Thus if the entire shell of this species were as soft as the inner layer this species too would be unknown in the Selma.

[1] S. G. Morton, *Synopsis of the Original Remains of the Cretaceous Group of the United States* (1834), p. 62.

THE RIPLEY FORMATION

The Ripley formation has the greatest areal distribution of any of the Upper Cretaceous formations in Tennessee. It is extensively developed both in the northern and southern part of the state. It outcrops in a broad belt in general along the Tennessee-Mississippi divide, a hilly and sandy area with little fertility or agricultural productiveness. In certain localities this formation is highly fossiliferous and contains an abundance of beautifully preserved animal and plant remains, but these are rather exceptional, for the Ripley of Tennessee is made up largely of non-fossiliferous sands and clays. In the southern part of the state the Ripley formation has been segregated into the following lithologic and faunal members or horizons: Owl Creek horizon or member; McNairy sand member; ferruginous clay horizon or member; Coon Creek horizon or member. In the central and northern parts of the state the Owl Creek member and the ferruginous clay member lose their identity and become a part of the McNairy sand member which constitutes by far the major portion of the Tennessee Ripley.

The Coon Creek horizon or member in the northern part of the state consists of ferruginous sands with few or no fossils, but in the southern part of the state it is glauconitic and fossiliferous. In some localities it contains beds of sandy marl which have yielded a very large fauna of beautiful and unusually well-preserved marine fossils. An announcement of the discovery of these fossils and a somewhat detailed description of the Coon Creek locality together with some preliminary observations on the fauna were published in the March, 1917, number of the *Johns Hopkins University Circular*. Figures and plates of this fauna of about three hundred and fifty species are now being made for a monograph report by the author to be published by the United States Geological Survey.

The occurrence of so many well-preserved shells in deposits as old as the Cretaceous is uncommon. No other single locality in the American Cretaceous, that has yet been studied, has produced so large an assemblage of such excellent fossils, which even rival best Cretaceous collections from any of the well-known European or Indian localities. Some of the well-known Cretaceous localities

that have yielded prolific faunas which may be cited for comparison and reference are: Owl Creek, Mississippi,[1] Ripley formation; Eufaula, Alabama,[1] Ripley formation; Patula Creek, Georgia,[1] Ripley formation; Snow Hill, North Carolina,[2] Black Creek formation; Brightseat, Maryland,[3] Monmouth formation; Mount Laurel, New Jersey,[4] Monmouth formation; Fox Hills, Moreau River, etc., western interior,[5] Montana formation; Huerfano Park, Pugnellus Sandstone, Colorado,[6] Colorado formation; Phoenix, Oregon,[7] Lower Chico series; Queen Charlotte Islands, Canada,[8] Chico series; Ferrocarril de Tampico á San Luis Potosí, Mexico,[9] Lower Senonian; Lastro, Sergipe, Brazil,[10] Senonian; Quiriquina, Chili,[11] Senonian; Pondoland, South Africa,[12] Senonian; Chargeh Oasis, Libyan Desert,[13] Danian; Central Tunis, Africa,[14] Cenomanian Atherfield, England,[15] Wealden; Blackdown, England,[15] Upper Greensand; Aachen, Germany,[16] Senonian; Kunroed, Belgium,[17]

[1] L. W. Stephenson, *U.S.G.S. Prof. Paper 81*, Tables 2, 8; T. A. Conrad, *Jour. Acad. Nat. Sci.*, Vol. III, 2d Ser. (Phila., 1858), pp. 323–36; Vol. IV, 2d Ser. (1860), pp. 275–98.

[2] L. W. Stephenson, *Upper Cretaceous Paleontology of North Carolina*. Manuscript in press; T. A. Conrad, *Rept. Geological Survey of North Carolina*, Vol. I, App. A (1875).

[3] J. A. Gardner, *Maryland Geological Survey, Upper Cretaceous Volume* (1916).

[4] Stuart Weller, *Pal. New Jersey*, Vol. IV (1907), pp. 128–36, etc.

[5] Meek and Hayden, *U.S.G.S. Terr.*, Vol. IX (1876).

[6] T. W. Stanton, *U.S. Geol. Sur. Bull. No. 106* (1893).

[7] F. M. Anderson, *Proc. Cal. Acad. of Sci.*, Vol. II, 3d Ser. (1902).

[8] J. F. Whiteaves, *Geol. Sur. Can. Meso. Fos.*, Vol. I (1876).

[9] E. Böse, *Instituto Geologico de Mexico*, Bol. 24 (1906).

[10] C. A. White, *Archivos de Museu Nacional do Rio de Janeiro*, Vol. VII (1888).

[11] O. Wilchens, *Neues Jahrb. für Min., Geol., und Pal.*, Band XVIII (1904), p. 272.

[12] H. Woods, *Ann. South African Museum*, Vol. IV, Part VII (1906).

[13] A. Quass, *Beitrag zur Kenntnis der Fauna der obersten Kreidebildungen in der Libyischen Wüste* (München, 1902).

[14] L. Pervinquière, *Etudes de Paléontologie Tunisienne*, Vol. I and II (Paris, 1912).

[15] H. Woods, "Cret. Lamel.," *Pal. Soc. London*, Vols. I, II (1899–1913).

[16] E. Holzapfel, *Palaeontographica*, Bände XXXIV, XXXV (1888, 1889).

[17] F. Kaunhowen, *Palaeontologische Abhandlungen*, neue folge, Band IV (1897).

Maestrichtian; Le Mans, France,[1] Cenomanian; Gosau, Austria,[2] Turonian; Conarapollia, India,[3] Arrialoor group.

An analysis of the Coon Creek fauna and comparisons with related faunas will appear in the monograph report. A new species of Scaphites closely related to the well-known form *Scaphites nodosus* Owen[4] is perhaps as diagnostic and as representative a form as any single species of the Coon Creek fauna that might be mentioned. The *nodose* group of Scaphites are widely distributed in the marine Senonian deposits of the Upper Cretaceous of the world. They have been extensively studied and are an important factor in intercontinental correlations[5] of these deposits.

The ferruginous clay horizon or member of the Ripley is well exposed in a cut on the M. and O. R.R. just south of Falcon in McNairy County. This is a series of stratified micaceous clays about one hundred feet in thickness with numerous concretions of limonite which are very conspicuous on the eroded slopes in the central part of McNairy County. A scant and dwarfed marine fauna has been obtained from this clay in the southern part of the state. Toward the north this clay becomes sandy, loses its identity, and merges into the McNairy sand.

The McNairy sand member is a thick series of non-marine sands and clays with a few irregular occurrences of quartzites. As is shown on the accompanying map the McNairy sand covers a wide belt of the Cretaceous area and is equally developed in both the northern and southern portions of the state. This member was first differentiated and described by Stephenson[6] in 1914. It is typically exposed at a cut on the Southern Railroad near

[1] A. d'Orbigny, *Paléontologie Française, Terrains Crétacés* (Paris, 1840–60).

[2] F. Zekeli, *Abhandl. der k.k. Geol. Reichs.*, Band I (1852); K. A. Zittel, "Die Bivalven der Gosaugebilde," *Denkschr. d.k. Akad. d. Wissensch. Wien. Math.-nat. classe*, Vols. XXIV and XXV (1865–66).

[3] F. Stoliczka, "Pal. Indica, Cretaceous Faunas, South India," *Geol. Survey India* (1865–70).

[4] D. D. Owen, *Rept. Geol. Sur. Iowa, Wis., Minn.*, p. 580, Table 8, Fig. 4 (1852); F. B. Meek, *U.S.G.S. Terr.*, Vol. IX, pp. 426–30, pls. and figs (1876).

[5] F. Frech, "Ueber Scaphiten," *Centralblatt Min., Geol., Pal.*, No. 18 (1915), pp. 553–68; No. 21, pp. 617–21.

E. Kayser, *Lehrbuch der Geologie*, Teil II, 5. Auf., pp. 534–62 (1913).

[6] L. W. Stephenson, *U.S.G.S. Prof. Paper 81* (1914).

Cypress, McNairy County. Clay is mined from the McNairy sand at several localities in Carroll and Henry counties.[1] Conspicuous large masses of quartzite or very hard, fine-grained, white sandstone of irregular occurrence are found at several isolated localities in Henderson, Carroll, and Henry counties in the lower part of the McNairy sand member. The more important quartzite localities are shown on the accompanying map and section. These masses are exceedingly resistant to erosive agencies and are often left lying bare on the surface after the softer sands and clays which formerly inclosed these masses have been washed away. They occur in irregular, cavernous, and often grotesque shapes that attract the attention of travelers and the natives in these regions. The well-known "hollow rock" at Hollow Rock Junction in Carroll County has served as a landmark since early settlers first went into that part of the state. The most extensive occurrences of this quartzite are two miles south of Dollar in Carroll County where masses as large as a two-story house may be observed in an area of two or three square miles. The origin of these masses is due to the cementation of local accumulations of very fine and pure quartz sands deposited along with the other McNairy sediments. Large masses of highly ferruginous hard sandstones are common in the Ripley, but the quartzites under discussion are characterized by a very low iron content. Similar occurrences of quartzites are known in the Eocene of Tennessee, Arkansas, and Mississippi.

Fossils are quite rare in the McNairy sand, and the few that have been known until quite recently were about twelve species of plants collected from near Selmer[2] and Big Cut[2] in McNairy County and three species from the southeastern part of Henry County.[2] In 1919 Schroeder noted the abundance of fossil leaf impressions in the Cooper clay pit[3] near Hollow Rock, Carroll County, but made no collection of these plants. During the latter part of the summer of 1919 the writer made large collections of

[1] W. A. Nelson, *Tenn. Geol. Sur. Bull. No. 5* (1911).

[2] E. W. Berry, *Torrey Bot. Club Bull. 43*, pp. 283–304 (1916); *U.S.G.S. Prof. Paper 112*, pp. 38, 39 (1919).

[3] R. A. Schroeder, "Res. of Tenn.," *Tenn. Geol. Sur.*, Vol. IX, No. 2 (1919), p. 154.

fossil plants from the Cooper clay pit and from some new localities, namely, three miles south of Mifflin in Chester County, near Beuna Vista in Carroll County, and from the Perry Place, ten miles east of Paris on the Manlyville Road, in Henry County. These collections have all been submitted to Professor Berry, and he is now completing a monograph report on this heretofore unknown, large, Ripley flora of more than one hundred and twenty species. The majority and the best specimens of this plant material came from the Perry Place. This locality is a small gully exposure of a lens of clay several feet in thickness on a farm belonging to Dr. J. R. Perry. The fossil leaves occur in a two-foot layer of dark brownish clay in the very bottom of the gully. This locality is about eighteen miles southeast of Puryear and about the same distance northeast of the Grable clay pit. Puryear is an Eocene plant locality made famous by the recent studies of Professor Berry,[1] who has collected and described from the Wilcox clays of Puryear the largest and most beautiful fossil flora known in America. The Grable clay pit is a recent opening in the Wilcox clay about twenty miles southwest of Puryear and contains a great wealth of fossil plants. Due to the recent workings at the Grable and due to the filling in of some of the old classic pits, there is at present no locality in west Tennessee where so many beautiful fossil plants can be obtained as at the Grable pit and the neighboring Adkins pit. Of the Ripley plant localities next to the Perry Place in importance is the Cooper clay pit. All the McNairy plant localities are shown on the accompanying map and diagrammatic section.

Stratigraphically above the McNairy sand member in southwestern McNairy and eastern Hardeman counties is the Owl Creek horizon or member. This is a series of micaceous sands and marls about fifty feet in thickness in Tennessee that contain a portion of the Owl Creek marine fauna. About fifty species have been collected at Trimms Mill and other localities on Muddy Creek in Hardeman County. Among these is the Owl Creek form, *Scaphites iris* Conrad.[2] This northern extension of the Owl

[1] E. W. Berry, *U.S.G.S. Prof. Paper 91* (1916).

[2] T. A. Conrad, *Jour. Acad. Nat. Sci.*, Vol. III, 2d Ser. (Phila., 1858), p. 335, Pl. 35, Fig. 23.

Creek beds does not extend far into Tennessee. It is merely one of the major oscillatory stages of the retreating Ripley sea as it withdrew slowly from the northern part of the Mississippi embayment area.

The general stratigraphic and areal relations of the Tennessee Upper Cretaceous are best summarized on the accompanying map and diagrammatic section. These show the positions of the large Ripley faunas and floras with reference to the rest of the Tennessee Cretaceous. The most important scientific results of the recent studies of the Tennessee Cretaceous are the unearthing of the Coon Creek fauna and the Perry Place and Hollow Rock flora. These abundant and excellent animal and plant remains are of nearly the same age and at the base of the Ripley. They not only mark definitely the lower Ripley with two different lines of evidence, making this a very important horizon for reference in subsequent studies and intercontinental correlations of the Upper Cretaceous, but also these well-preserved remains furnish certain biological evidences that are of some importance in the systematic classification of a few of the ancient animals and plants of Cretaceous times.

THE CHESTER SERIES IN ILLINOIS

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PART II

UPPER CHESTER GROUP

Tar Springs sandstone.—Like the Lower and Middle Chester groups the Upper Chester is initiated by an important sandstone formation which is named the Tar Springs. This name was first used by Owen many years ago for a sandstone in Breckinridge County, Kentucky, and has been revived by Butts[1] at a recent date. This sandstone is a persistent formation across Hardin, Pope, and Johnson counties, as far as the detailed mapping has been carried, and it doubtless continues into Union County. The sandstone is variable in character. In some places in the area which it occupies it is as massive and as conspicuous a cliff maker as the Cypress; this is especially true in some portions of Hardin County. Elsewhere it is nearly all thin-bedded. Much of the sandstone is conspicuously cross-bedded. Throughout much and perhaps the whole of the Chester belt across the southern counties, the Tar Springs sandstone is divided into an upper and lower member by a persistent shale bed, which has associated with it in widely separated localities a thin layer of impure coal, in some places only an inch or two in thickness but elsewhere a foot or more. The more massive layers of the sandstone resemble the Cypress and Hardinsburg in color and texture, but in much of Pope and Johnson counties, where the formation is more thinly bedded, it is distinctly darker brown than any of the older Chester sandstones.

The thickness of the Tar Springs sandstone varies considerably. In Hardin County it is one hundred feet or more thick, perhaps as much as one hundred and fifty feet locally, but it diminishes to

[1] *Mississippian Formations of Western Kentucky* (1917), p. 103.

the west, and in western Johnson County there are places where it is apparently not more than forty feet. In tracing the horizon into the Mississippi Valley counties, the Tar Springs disappears entirely, there being not even such a thin discontinuous sandstone horizon as that which represents the Hardinsburg, the position of the sandstone being occupied by a plane of unconformity above the Upper Okaw or Glen Dean limestone.

Vienna limestone.—The Vienna limestone is named from Vienna, Johnson County, Illinois, where the formation is exposed in some of the streets of the town, and in an old quarry just west of the town. As it is commonly exposed, the Vienna exhibits two rather distinct facies, an exceedingly siliceous limestone in the lower portion of the formation, and a shale member above. In places the limestone seems to comprise the greater portion of the formation, but in other localities it is mostly all shale, with but little of the limestone present. As already stated the limestone is remarkably siliceous. The silica is in part in the form of chert layers, and in part is finely disseminated through the limestone. On weathering, the limestone with the disseminated silica loses the lime by solution, and the residuum is a light, yellowish-brown, porous rock, which on first inspection resembles a fine-grained sandstone, but which contains no sand grains whatever. The chert of the formation is quite persistent in character, the beds commonly being from one to four inches thick and quite regular. Near the surface the upper and lower portions of these chert beds have been subjected to some decomposition and are much lighter in color for a fraction of an inch in depth than is the deep chocolate brown of the central portion of the beds. As the limestone with the chert layers is removed by weathering, the cherts fracture into subcubical masses with two light-colored surfaces, and occur in abundance in the residuum. Less commonly there are some thicker chert beds, six to eight inches, which are more or less porous in character. The peculiar character of the weathered products of the Vienna limestone make it about the easiest to recognize of any of the limestone formations of the whole Chester series. The shales of the Vienna are black, fissile, and non-calcareous.

The siliceous limestone facies of the Vienna has been recognized from eastern Pope County, across Pope and Johnson counties, and into the eastern part of Union County, except where the formations are interrupted by faulting. The black shale facies of the same formation probably extends eastward beyond Pope County into Hardin. It has been recognized considerably farther west in Union County than the limestone, but it is not unlikely that the limestone will be found to extend farther in that direction when the detailed mapping is carried across Union County.

North of Golconda, in Pope County, a measured section through the Vienna formation gives a thickness of seventy feet. This is perhaps the maximum thickness that is known, and the average thickness throughout the area occupied by the formation is probably about sixty feet, perhaps becoming considerably thinner than this to the east.

The fauna of the Vienna limestone has certain characteristics which distinguish it from the other limestones of the Chester series. The *Prismopora* so characteristic of the Glen Dean limestone is present somewhat commonly in the Vienna in places, but it has never been observed to be so abundant as it is in some localities in the older formation. Associated with the *Prismopora* there is found somewhat rarely the pelecypod species *Sulcatopinna missouriensis*, which is highly characteristic of the next higher limestone in the Chester series, the Menard. This notable mingling of the Glen Dean and Menard species is perhaps the leading characteristic of the fauna as a whole, although further studies of the fauna must be made.

In the absence of any representative of the Tar Springs sandstone in the Randolph County section, the determination of the Vienna equivalent in the section, if there is such an equivalent, is rendered somewhat difficult. There is no lithologic unit present in Randolph County similar to the siliceous limestone of the Vienna, and no fauna has been recognized in which the Glen Dean and Menard forms are associated. There is, however, locally at least, lying above the Okaw limestone and beneath the typical Menard, a conspicuous black-shale horizon, which may be a continuation of the black shale of the Vienna in the southern

counties. Further field studies may serve to prove or disprove this suggestion.

Waltersburg sandstone.—On Bay Creek, between Simpson and Grantsburg, near the line separating Pope and Johnson counties, there is a conspicuous sandstone formation overlying the Vienna limestone. The maximum thickness of this sandstone along Bay Creek is about sixty or seventy feet, but it is reduced in thickness both to the east and to the west. In an easterly direction the sandstone has been recognized at its proper position in the section nearly to Grand Pierre Creek in eastern Pope County. To the west it is known to extend, but much reduced in thickness, nearly to the Johnson–Union County line, and it may be found to continue into Union County. As viewed along an east-west section across the southern counties of Illinois, this formation is a lenticular body of sandstone with a lateral extent of nearly forty miles. The extent of the formation in a north-south direction is not known.

The importance of this unit in the Chester section was first recognized in Pope County, northwest of Golconda, where it is well exposed in the road just north of Waltersburg, from which locality the formation has been named, although it is by no means as thick at this point as it is farther west. In its area of maximum development the Waltersburg is a massive, cliff-forming sandstone, not conspicuously different in character or appearance from portions of the Bethel, Cypress, Hardinsburg, or Tar Springs sandstones. Where the formation approaches its lateral limits to the east and west, it is a thinly bedded, rather impure sandstone, in layers two or three inches thick, which are commonly distinctly jointed in two directions, one set of joints being placed at intervals of two or three inches, the other at a foot or more. These two systems of joints cause the rock layers to break up into elongate, splinter-like blocks which are rather characteristic. There are places where the entire formation is represented only by two or three feet of sandstone of this character, situated between the black shale of the Vienna below and the calcareous shales and limestones of the Menard above.

No fossils have actually been observed in the Waltersburg, but trunks of Lepidodendron, such as are found in the other Chester sandstones, may be expected.

Menard limestone.—The Menard limestone was originally named from the exposures in the Mississippi River bluffs at Menard, Illinois.[1] The formation is a persistent one in the Chester section of the Mississippi River counties of Illinois, from the point where the formation is first exposed from beneath the overlapping Pennsylvanian formations in Randolph County to where it passes beneath the surface in the Mississippi River bluffs in Jackson County. In the Mississippi River counties, where it was first described, the Menard was found to rest upon the Okaw limestone, the two limestones being rather sharply differentiated by both lithologic and faunal characters. It is now known that two important sandstone formations, the Tar Springs and the Waltersburg, are intercalated between these two limestone horizons in the Chester section of the southern counties, and also the Vienna limestone, unless it can be shown that this formation is represented by the black-shale bed that is at least locally present in Randolph County between the top of the Okaw limestone and the base of the more typical portion of the Menard.

In its typical expression the Menard is evenly bedded in layers about one foot, more or less, in thickness. The individual beds are separated by thin shaly seams or by beds of shale up to several feet thick, the surfaces of the limestone layers being distinctly hummocky. The limestone itself is commonly compact in texture, almost lithographic in places, hard and rather tough, breaking with a splintery or conchoidal fracture. The color of the limestone is commonly light gray, and the weathered surfaces are smooth in most places. These characteristics are quite in contrast with the crystalline beds of the Okaw limestone, with its more roughly weathered surfaces. An occasional bed of crystalline limestone is met with in the Menard, which might be mistaken for the Okaw if it were found alone.

Where the Menard limestone is exposed in the Chester belt across the southern counties, it can be easily traced across Union, Johnson, Pope, and Hardin counties, except where it is interrupted by faulting. Throughout this belt the limestone exhibits essentially the same lithologic characters as in Randolph County,

[1] Weller, *Trans. Ill. Acad. Sci.*, Vol. VI (1914), p. 128; also *Ill. State Geol. Surv.*, Monog. I (1914), p. 28.

except that the freshly broken rock is commonly darker in color, in some places nearly black, and it is associated with a greater amount of shale, one of the most calcareous shale beds at the base of the formation being highly fossiliferous. Near or perhaps at the very base of this limestone in the southern counties, a thin seam of impure coal, not more than two or three inches thick, has been observed in a number of localities and is perhaps a persistent band. A small amount of chert is present in the Menard, by no means so great a quantity as in the Vienna, but distinctly more than is commonly present in the Middle Chester limestones.

The fauna of the Menard possesses many characteristics common to the Chester formations generally, but certain other features differentiate it quite sharply from those of the earlier limestones of the series. The species of the two genera *Spirifer* and *Composita* show a notable change in the Menard faunas from the earlier forms, in being larger and more robust in form. The typical examples of *Spirifer increbescens* are initiated in this horizon, and the typical *Composita subquadrata* takes the place of *Composita trinuclea*, which was the usual form in the older limestones. A very characteristic member of the fauna is the pelecypod *Sulcatopinna missouriensis*, which occurs in most Menard collections; in places it is very abundant, commonly standing vertically in the limestone strata, probably the position it occupied when living. This species occurs also in the Vienna limestone, but more rarely than in the Menard, where it is associated with the bryozoan *Prismopora serrulata*, which is unknown in the Menard. The most fossiliferous horizon in the Menard is the basal calcareous shale which is present in the southern counties, and which has been recognized across Hardin, Pope, Johnson, and Union counties. This bed is similar in character, both lithologic and faunal, irrespective of whether the underlying Waltersburg sandstone is thick, thin, or absent from the section. Among other forms which are commonly met with in this basal horizon is the blastoid *Pentremites fohsi*, and in the experience of the writer this species has been found in no other horizon.

The thickness of the Menard limestone in the Mississippi River counties commonly varies between sixty and eighty feet,

but in the Kiskaddon well, near Bremen, there are eighty-five feet of strata referable to the formation. The average thickness may be assumed to be about seventy-five feet. In the southern counties the formation is somewhat thicker. In one measured section north of Golconda it is essentially one hundred feet, and that seems to be about the thickness of the formation commonly represented in the southern belt.

Palestine sandstone.[1]—The Palestine is the first of the sandstone formations of the Chester series which is present with essentially equal development both in the Mississippi River counties and in the southern counties of Illinois. The sandstone resembles the other Chester sandstones in its general features, but in only a few regions does it include notably massive beds, though such beds are present in the vicinity of Chester, Illinois, where it has been quarried for building stone. In general this sandstone is rather thinly bedded, in some regions including much shale which is more or less arenaceous in character. As commonly exhibited, the color of this sandstone is somewhat paler than most of the older sandstones of the series, and much of it, at least, is rather finer textured. None of these characteristics, however, are persistent enough to enable the formation to be readily recognized by its lithologic characters, and the only sure means of identifying it is from its relations with either the underlying or overlying limestones. Fossil tree trunks of the genus *Lepidodendron* occur more commonly, perhaps, in the Palestine than in any other sandstone of the Chester series, and one specimen six or seven feet long has been observed. No other fossils have been seen in the formation.

The thickness of the Palestine is not so great as that of some of the earlier Chester sandstones, although its geographic distribution is wider. In two measured sections in the Mississippi River counties the formation is sixty and sixty-seven feet respectively. In some other sections it is probably somewhat greater than this, perhaps as much as eighty feet. In the southern counties the maximum thickness of the formation is eighty feet, but in

[1] Weller, *Trans. Ill. Acad. Sci.*, Vol VI (1914), p. 128; also *Ill. State Geol. Surv.*, Monog. I (1914), p. 29.

places it is considerably less, perhaps being as thin as forty feet in places. The average thickess of the formation throughout its entire extent is approximately seventy feet.

Clore limestone.—The Clore limestone was first described in Randolph County[1], and at the time it was believed to be the highest formation in the Chester series, but later observations have shown that it is succeeded by still another sandstone, and this again by a higher limestone formation. In many places the Clore really includes a larger amount of shale than it does limestone, locally the shale being much in excess of the limestone, and some ledges of the limestone itself are more or less shaly. The limestone beds of the formation exhibit a considerable amount of variation, some being compact and fine grained, others being shaly, some are hard and apparently siliceous, and a few beds are more or less crystalline. Nearly all of the limestone beds are more or less impure. The shale beds are almost entirely argillaceous or are more or less calcareous, the more calcareous beds having thin, platy layers of limestone imbedded in the shale. In the Mississippi River counties there is apparently a greater amount of limestone in the formation than in the southern counties, but wherever the formation occurs it is difficult to determine in detail its true composition, because of its non-resistent character and the consequent covering of surficial material.

The Clore is not a thick formation. Its thickness in two measured sections in the Mississippi River bluffs below the mouth of Marys River is between thirty and forty feet. In places, where it is the uppermost formation in the Chester series, it varies in thickness from forty feet down to nothing, due to the erosion of the higher beds. In the southern counties of the state the Clore is nowhere the highest formation of the Chester, and its lower and upper limits can rarely be determined with exactness. Furthermore both the lower and upper limits of the formation have nowhere been determined in one and the same section with any degree of accuracy. These conditions make the determination of the thickness of the formation in these counties rather uncertain,

[1] Weller, *Trans. Ill. Acad. Sci.*, Vol. VI (1914), p. 129; also *Ill. State Geol. Surv.*, Monog. I (1914), p. 29.

but numerous observations seem to establish a limit of about forty feet for the interval between the underlying and overlying sandstones in which it must be contained, which seems to establish a nearly uniform thickness in both of the two Chester areas of the state. As the formation is traced eastward, in the eastern part of Pope and in Hardin County, the Clore seems to become thinner even than the forty feet of the region to the west.

The fossils of the Clore formation are numerous in places, and, like the faunas of all the other limestones of the Chester series, it possesses certain rather distinctive features. The general composition of the fauna is similar to that of other Chester horizons, being made up largely of bryozoans and brachiopods, with the axes of *Archimedes* and numerous species of Fenestellids being conspicuously present. The most significant feature of the fauna, however, is the abundance of small, cylindrical, branched bryozoa of the genus *Batostomella*, *B. nitidula* apparently being a conspicuous species. The fossils are most abundant upon the surfaces of thin limestone layers imbedded in some of the shales, and one such horizon is rather persistently present near the middle of the formation throughout most of the southern belt, and perhaps also in the Mississippi River counties as well. It is from this layer that the bryozoan-covered slabs of the Clore can be collected in great numbers. Among the brachiopods of the Clore fauna, large forms of *Spirifer increbescens* and *Composita subquadrata*, similar to those in the Menard limestone, are common in some localities.

Degonia sandstone.—During the earlier field studies in Randolph County, it was believed that the massive sandstone formation which was found to overlie the Clore limestone was the basal member of the Pennsylvanian, but during the progress of the field mapping of the Campbell Hill Quadrangle in the summer of 1919 by J. M. Weller, it has been found that this sandstone is succeeded by a still higher Chester limestone, which in turn is overlain by the true lower Pennsylvanian Pottsville sandstone filled with pebbles in many places. This sandstone, now known to be Chester, is especially well exhibited in the walls of several tributaries to the Mississippi River in Degonia Township of Jackson County, Illinois, and the name has been chosen from these exposures.

In southeastern Randolph, and in Jackson County to the valley of the Big Muddy River, the Degonia is a conspicuous cliff-forming sandstone, well exposed in the Mississippi River bluffs and in some of the tributaries to the Mississippi. In its massiveness the formation is perhaps more nearly comparable with the Cypress sandstone of the southern counties than with any other Chester sandstone, and where it is best exhibited it is commonly exposed in vertical cliffs forty or fifty feet in height, although the total thickness of the formation is considerably greater than this. The sandstone is somewhat coarser than most if not all of the other Chester sandstones, and is so much like some of the lower Pottsville beds of the adjoining regions, in localities where such beds are free from pebbles, that it is impossible, in places where the Kinkaid limestone is wanting, to always establish the line separating the Degonia from the Pottsville. Indeed this whole sandstone formation was considered to be Pottsville by Shaw, and was so mapped in the Murphysboro Quadrangle.[1]

In some sections, and perhaps in all, the whole of the Degonia is not as massive as the conspicuous cliff-making beds of the formation, but consists of thinly bedded or almost shaly sandstone in which the individual beds are undulating or curling, the undulations being irregular in character and having a width of only a few inches and a height of an inch or two. In places the more massive layers and the thinly bedded layers are arranged alternately in the sections, the units being variable in thickness up to fifteen or twenty feet. The total thickness of the Degonia sandstone throughout its extent in Randolph and Jackson counties varies only slightly from one hundred feet except where it is the highest formation in the Chester series and has been subjected to pre-Pennsylvanian erosion.

Of all the Chester formations the Degonia sandstone is most nearly continuous from the Mississippi River counties into the more southern area of the state, and further field studies may establish the complete continuity of the formation from one area into the other. In Jackson County the formation has been traced southward to the valley of the Big Muddy River. It is

[1] *Geologic Atlas of U.S.*, Folio No. 185 (1912), p. 6.

undoubtedly present in the Mississippi River bluffs south of the Big Muddy, and probably can be traced to northwestern Union County, where it will connect with the belt across the southern counties.

In the southern counties the Degonia is continuously exposed from Union to Hardin counties. In Union County the thickness of the formation is in excess of seventy-five feet; at Simpson, in eastern Johnson County, it is at least one hundred feet thick; but farther east, across Pope and Hardin counties, it probably is somewhat reduced from the maximum thickness. There are places in Union County where the formation is fully as massive as in any of the sections in Jackson County, but to the east it becomes somewhat more thinly bedded, although massive layers are present in the formation throughout its entire extent in the state. In general, in its more eastern extension, the Degonia sandstone is rather paler in color and of finer texture than farther west, and in many places it resembles the Palestine somewhat closely.

The fossils of the Degonia sandstone are like those of the other Chester sandstones. The only forms that have been recognized are plant remains, and of these the *Lepidodendron* trunks are most commonly met with.

Kinkaid limestone.—The highest formation in the Chester series of Illinois is the Kinkaid limestone, named from the excellent exposures on Kinkaid Creek, in Jackson County. The formation is well developed in southeastern Randolph and in Jackson counties, and continues across the southern counties from Union to Hardin.

In its lithologic characters the Kinkaid more closely resembles the Menard than any other Chester limestone. It has been deposited in the same sort of regular beds about a foot, more or less, in thickness, the individual beds being separated by thin shaly seams, and the surfaces being distinctly hummocky. Many small exposures of the Kinkaid would be indistinguishable from similar exposures of Menard if the stratigraphic relations could not be determined. Some of the beds of the Kinkaid possess the same sort of compact, hard, close-textured limestone that is so commonly present in the Menard, but on the whole the Kinkaid probably includes a larger amount of somewhat more crystalline limestone

than the Menard. In Randolph and Jackson counties no notable shale members have been recognized in the formation, and no conspicuous chert layers have been seen in place, although in some localities the residuum from the formation shows a considerable amount of broken chert.

In the southern counties the Kinkaid limestone is similar in character to the exposures in Jackson County; this is especially true in Union County, but as the formation is traced to the east it is found to include important shale beds and some very notable chert horizons. A very characteristic shale bed in the Kinkaid in Johnson and Pope counties, and perhaps also in Hardin, near the base of the formation and some eight or ten feet thick, is a dark-red color. There are perhaps other red-shale horizons in the formation. Other shale beds are of a distinctly olive-green color, and these red and green shales are a very characteristic feature of the formation in the more eastern portion of its extent. In this same region there are one or more remarkable chert horizons in the Kinaid. The more important of these is a massive bed three or more feet thick, commonly rather light colored, and in places with a slightly greenish tint. The resistant character of this chert makes it a conspicuous feature in places in the residuum from the formation as seen along roadsides, in stream beds, and on hillsides. In places subcubical masses of the chert a foot or more in dimension are strewn over the surface where the bed is present. There are other less conspicuous chert beds, some of them dark colored and similar in character to the chert that is so abundant in the Vienna limestone. The limestone layers of the Kinkaid in this more eastern region are quite similar in lithologic character to the beds in Randolph and Jackson counties.

The thickness of the Kinkaid limestone exhibits considerable variation due to the fact that it is the highest formation of the Chester series, and has consequently been subjected to the pre-Pennsylvanian erosion. Its greatest thickness in Jackson County is in excess of fifty feet, and it may vary from this maximum thickness to nothing at all, for in places the Pennsylvanian strata rest upon the Degonia sandstone. In the southern counties the formation is also variable in thickness, but on the whole it is notably

thicker than it is north of Big Muddy River. At one locality in the bluffs northwest of Buncombe, in Johnson County, the limestone is about one hundred and forty feet thick and in the entire belt across the state the minimum thickness seems to be not less than sixty or seventy feet.

The fauna of the Kinkaid limestone, so far as it is known, is not so prolific as is that of several of the older limestones in the Chester series, but it resembles these earlier faunas in its general characters, consisting, as it does, of the same genera of brachiopods bryozoans, and blastoids. The pelecypod *Sulcatopinna missouriensis*, which is so characteristic of the Menard, is also present in the Kinkaid, and associated with it is the large form of *Spirifer increbescens*. The specimens of *Composita*, however, which have been met with in the Kinkaid, are of the smaller type, like those in the Middle and Lower Chester limestones. A form that is very common in the Kinkaid is a species of *Martinia*, a genus which is commonly wanting in other Upper Chester faunas, and is only locally common in the Middle and Lower Chester horizons. The bryozoans have nowhere been found to be so abundant or so well preserved in the Kinkaid as they are in the earlier Chester limestones, but those that are present are members of the same genera as are represented elsewhere, and most of the species are also believed to be present in the lower horizons.

GEOLOGICAL CROSS-SECTION

The relations of the several Chester formations in Illinois which have been described in the preceding pages are shown in the accompanying diagrammatic section. This section is intended to illustrate the sequence of beds from Hardin County at the southeast to Randolph and Monroe counties at the northwest. The sandstone units are shaded in the diagram, the limestone-shale units being left blank. The diagram has been constructed as if the upper units of the formational succession were continuous to the extreme northwestern extension of the Chester beds in St. Clair County. This is not the actual condition, however, for the entire series of beds is truncated by the Pottsville, so that these basal Pennsylvanian strata, in passing northward from Randolph

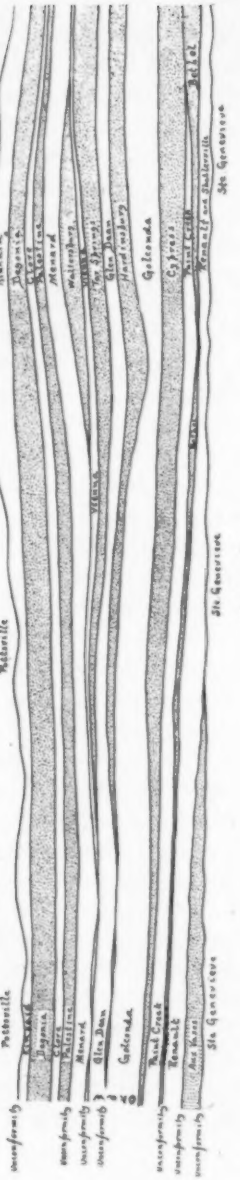

FIG. 1

through Monroe and into St. Clair counties, successively overlap the truncated Chester formations until they rest upon the Ste. Genevieve and St. Louis limestones whose position is beneath the Chester.

GEOLOGICAL HISTORY

In order to appreciate properly the historical relation of the Chester series in the Illinois basin to the Mississippian as a whole, it is desirable to outline somewhat briefly the succession of events which are recorded in the Lower Mississippian or Iowa series. The stratigraphic units which are commonly recognized in this series in the Mississippi Valley are as follows:

7. Ste. Genevieve limestone
6. St. Louis limestone
5. Spergen limestone
4. Warsaw limestone and shale
3. Keokuk limestone
2. Burlington limestone
1. Kinderhook group

Throughout this basin the oldest of the Mississippian formations belonging to the Kinderhook group rest unconformably upon whatever beds underlie them, unless possibly there may be a continuity of sedimentation from Devonian time in southeastern Iowa. There is some reason to believe that the oldest Kinderhook

beds at Burlington, Iowa, the blue shales beneath the Chonopectus sandstone, are continuous with the Sweetland Creek shales which commonly have been placed in the Upper Devonian. However, the Sweetland Creek shales are unconformable upon the beds beneath them, and it is possible that the whole of the Sweetland Creek shale should be placed in the Mississippian. This condition of unconformity of the Kinderhook upon underlying formations of various ages persists entirely around the Ozark region of Missouri and northern Arkansas. This situation shows that preceding Kinderhook time the waters were withdrawn from the Mississippi Valley basin, at least north of the Ohio River, and possibly were withdrawn from the entire continent. The details of the first advance of the Mississippian waters cannot be discussed in this place, but the sediments recording this epoch are exceedingly various in character, there being sandstones, shales, and limestones. As the waters advanced the Ozark land mass was at last largely or perhaps wholly submerged, and the mainland shore line of the Illinois basin crossed northern Illinois or southern Wisconsin and continued westward into Iowa. The position of this shore line was certainly north of Chicago, as is evidenced by the typical Lower Burlington fauna which has been recorded from the northern part of that city.[1] At this time the waters covering southeastern Iowa, the Ozark region of Missouri, and the adjacent parts of Illinois were quite free from land wash, and the very pure Burlington limestone was being deposited throughout this region. During Keokuk time there was a shifting of the northern shore line in a southerly direction, to such a position that a certain amount of clastic material was washed into that part of the sea which covered southeastern Iowa and the adjacent parts of Missouri and Illinois. The presence of this land wash is shown in the shaly beds which are present in the more northerly Keokuk exposures, a lithologic character which differentiates the Keokuk from the underlying Burlington limestone. Farther south in Illinois and in Missouri, both in the southeastern and southwestern parts of the state, at a greater distance from the shore line, these clastic beds are not present in the Keokuk, a condition that

[1] Davis, *Jour. Geol.*, Vol. XXV (1917), pp. 576–83.

makes the lithologic separation of the Burlington and Keokuk somewhat difficult.

In southeastern Iowa the land-derived sediments became more dominant in Warsaw time, although there is no stratigraphic break between the Keokuk and the Warsaw. Farther south in the Mississippi Valley basin, limestone deposition continued into Warsaw time, and in southwestern Missouri shale deposition of this age is absent or practically absent throughout the entire epoch. During Warsaw time, however, the northern shore of the basin continued its southward migration and by mid-Warsaw time it doubtless occupied a position somewhere between the southern border of Iowa and St. Louis, Missouri, and at this time the clastic sediment extended as far south as southeastern Missouri. The lower Warsaw only, therefore, was deposited in southern Iowa.

During Spergen time the sea readvanced to the north and again occupied what is now southeastern Iowa, where the Spergen limestone rests unconformably upon the Warsaw and where locally much or all of the lower Warsaw that had been deposited was eroded during the time when the shore line occupied a more southern position and when this part of Iowa was an area of dry land. At St. Louis and to the south the Warsaw sedimentation passed without interruption into the Spergen, but with the northward shifting of the shore line of the basin and the consequent greater remoteness of the region from the source of land wash pure limestone sedimentation without clastic materials of any sort was reinitiated.

During the later portion of Spergen time the shore line again shifted to the south, and must have occupied about the position of the late Warsaw land margin. This was followed by another shift to the north, which is evidenced by the unconformable relations of the lower St. Louis in Iowa, resting upon the eroded surface of the Spergen, the erosion in places having even cut through the Spergen, so that the higher formation rests upon beds of Warsaw age. Another oscillation of the shore line occurred in mid-St. Louis time, for the upper St. Louis beds in Iowa are separated by a distinct erosional unconformity from the lower St.

Louis, and this stratigraphic break is probably exhibited in the very greatly brecciated zone in the midst of the St. Louis limestone as far south as Alton, Illinois.[1]

In the region south from St. Louis, during all this time, the sedimentation had been continuous with no interruption whatsoever, showing that the Mississippian sea had continually occupied this southern portion of the basin. At the close of St. Louis time, however, a greater oscillation in the sea-level occurred, and the waters were withdrawn to some extent from the Ozark land as well as from Iowa and from all of the region between Iowa and Ozarkia. This withdrawal was only temporary, however, for the sea reoccupied the entire region and in it the Ste. Genevieve limestone was deposited unconformably upon the St. Louis. This sub-Ste. Genevieve unconformity is well exhibited near Ste. Genevieve, Missouri, and wherever the Ste. Genevieve limestone is present to the north of this locality to its most extreme northern outcrops in the Des Moines Valley of Iowa, near Fort Dodge. In a southeasterly direction from Ozarkia, however, in Hardin County, Illinois, sedimentation was continuous from the St. Louis into the Ste. Genevieve limestones, with no interruption of any sort, showing that the Mississippian sea continuously occupied this portion of the Illinois basin. The record of the extension of the Ste. Genevieve sea to the north and west of Ozarkia is obscured by the presence of younger sediments, but it is not unlikely that this ancient island was entirely surrounded at this time. Following Ste. Genevieve time the sea withdrew completely from the Illinois basin. Wherever the Chester formations are present their faunas appear abruptly, and wherever the sections have been examined critically there is evidence of unconformity between them and the underlying formations.

In summing up the history of the Illinois basin in Lower Mississippian time, the succession of events consists of oscillatory movements of the sea occupying the basin, these oscillations being exhibited by the shifting of the bounding shore line of the basin from north to south and back again to the north. The greatest

[1] These statements concerning the stratigraphic relations in southeastern Iowa are based chiefly upon the field observations of Dr. J. M. Van Tuyl.

northern extension of the basin was early in Mississippian time, the successive reoccupations of the region perhaps falling a little short each time of the previous one, and the successive withdrawals perhaps being a little greater each time until the final withdrawal at the close of Ste. Genevieve time. With each readvance of the sea to the north, however, essentially the same basin was reoccupied, so that the sea-pattern during all of this time, in the periods of greater submergence, remained practically the same, differing only in more or less minor details. During each interval of submergence in this period, the sea spread far to the north in Illinois, and westward in Iowa, and doubtless also in northern Missouri, surrounding and perhaps completely submerging at times the Ozark Island, and doubtless was connected with the seas which extended westward to the Rocky Mountain land.

With the return of the seas into the Illinois basin at the beginning of Upper Mississippian or Chester time, the conditions indicated by the sedimentary record were very different from those that had existed earlier. In the earlier period almost no sand deposits were accumulated anywhere in the region except in Kinderhook time, during the initial submergence of the basin, the only exception to this being the presence of the thin Rosiclare sandstone layer that is present in the Ste. Genevieve limestone in most sections. In Chester time, as has already been shown in the discussion of the successive formations, thick deposits of sand were accumulated, and most of the limestones were associated with large amounts of clastic material in the form of shales, these shaly Chester limestones being in strong contrast with the great thicknesses of nearly pure, massively bedded limestones of the Lower Mississippian. The original source of all these accumulations of Chester sand is not entirely clear. The Aux Vases sandstone at the base, which is thickest toward the eastern shore of Ozarkia and thins southeastwardly to nothing, may have been derived from the wearing away of some of the more ancient sandstones of Ozarkia, but such sandstones as the Bethel, Cypress, Hardinsburg, and Tar Springs, which are thick formations in southeastern Illinois and beyond in Kentucky, becoming much reduced or even absent altogether toward the shore of Ozarkia, could not have had such

a source. The sand of these formations may have been derived from the Appalachian land, still farther to the east. The Palestine and Degonia sandtones, which are almost equally thick clear across Illinois, belong in still another category. The Waltersburg sandstone differs in distribution from all of the others, being essentially restricted to an area about forty miles in width east and west, with an unknown extent in a north-south direction. This may be an accumulation in the form of a delta at the mouth of some stream from the north, which emptied into the Illinois basin, perhaps bringing the sand from some far-distant region. The origin of such sands as the Palestine and Degonia, which are more uniformly developed across the entire basin, and even some of the others which are less uniformly developed, may have been from more than one source.

The lateral distribution of the sands of the Chester series in the Illinois basin was doubtless through the agency of wave action along the shore line. During the stages of withdrawal of the waters in the basin, those shore sands, left high and dry, would be subjected to erosion and to transportation southward and redeposition, and to re-working in the next following advance of the waters. In this manner the same sand may have been worked over and over again in the shore deposits of the basin, a condition which may account in part at least for the great similarity between the several sandstone formations of the series.

The areal distribution of the Chester formations is very different from that of the Lower Mississippian. The northernmost exposures of the Chester is in the Mississippi River bluff in St. Clair County, Illinois, about one-half mile north of the St. Clair–Monroe County boundary line, opposite Bixby. Beyond this point the Chester formations are covered by the Pennsylvanian, but well records indicate that they swing off to the northeast from the last exposure to the vicinity of Decatur, Illinois, and from there continue in a southeasterly direction, passing into Indiana. These formations, therefore, were deposited in a basin lying between Ozarkia on the west and Cincinnatia on the east, with its northernmost extremity near the center of Illinois. This basin had a very different outline from that in which the Lower Mississippian

beds were laid down, the older basin extending much farther north and reaching westward into northern Missouri and Iowa, probably surrounding or submerging the Ozark land. The sea-pattern, then, of Chester time was quite different from that of the earlier Mississippian. The succession of sandstones and limestone-shale formations laid down in this basin in Chester time indicate a series of oscillations of the sea occupying the basin, comparable in a way to the oscillations in the much larger basin of Lower Mississippian time.

Throughout the alternating succession of Chester formations, the several units should be considered in pairs, each pair consisting of a sandstone formation below, passing upward into a limestone-shale formation. In a number of horizons in the series the sandstone formation clearly exhibits an unconformable contact with the underlying limestone, but in no case is there any evidence of unconformity between the sandstone and the overlying limestone-shale unit. Each one of these pairs doubtless represents one oscillatory advance and retreat of the waters of the basin, the lower sandstone unit in the pair being a transgressing formation associated with the advancing submergence, the limestone and shale deposition lagging behind the sand accumulation at a greater distance from the shore line. In so far as the sandstones lie unconformably upon the underlying limestone the magnitude of the oscillation has been sufficient to cause the waters of the basin to withdraw to a position south of the localities where observations upon surface outcrops have been possible. If the horizons of such unconformities could be traced southward toward the open sea of the period, they would presumably pass into entirely uninterrupted series of sediments, and if they could be followed still farther in the same direction the sandstone members in the succession of beds should disappear and a continuous limestone formation should represent the Chester series. At those horizons where no evidence of unconformity between the sandstone and the underlying limestone exists, the southernmost position of the retreating shore line of the basin was presumably somewhat north of the localities where the outcrops have been observed, and if the position of the ancient shore line at a period of emergence crossed the

present belt of outcrop of the formations, the unconformity might be looked for over part of the area and be entirely absent elsewhere.

With each readvance of the Chester sea in the Illinois basin, prolific invertebrate faunas occupied the waters, and their fossil remains have been preserved in the limestones and calcareous shales. These successive faunas were much alike in many respects, but as they are critically studied, it is found that each one of them possesses certain characteristics which serve to differentiate it from the others. Farther to the south or southwest, beyond the area of alternating land and sea conditions which obtained within the Illinois basin, the Chester fauna was doubtless undergoing a continuous, normal, evolutionary development, and the successive stages of this evolution, modified more or less by the local environmental conditions, are mirrored in the successive faunas of the several calcareous formations in the Chester section of the Illinois basin.

The succession of events that has been outlined has an important bearing upon the interpretation of the Mississippian period of North America. In his "Revision of the Paleozoic Systems," Ulrich[1] has split the Mississippian into two so-called systems, the Waverlyan below and the Tennesseean above, the line of cleavage between the two being placed between the Warsaw and Keokuk formations. From the evidence afforded by the Mississippi Valley section of the Mississippian, which is the type section of these strata, there is less reason for placing a major dividing line at this horizon than at almost any other position in the entire succession of formations, and there is no basis whatsoever for the recognition of the so-called Waverlyan and Tennesseean as systems. There are, however, many excellent reasons for making a lower and upper division of the Mississippian, the line of separation being at the base of the Chester series. This position is approximately at the horizon where Ulrich has subdivided his Tennesseean into the Meramecian and Chesterian, but even here he has made a grave error in including the Ste. Genevieve limestone in the Chesterian. This error was introduced by his failure to separate the Renault

[1] *Bull. Geol. Soc. Amer.*, Vol. XXII (1910), Plate XXIX, opp. p. 609.

limestone of western Kentucky and southern Illinois from the underlying Ste. Genevieve limestone. The Renault, or Renault-Shetlerville, actually lies unconformably upon the Ste. Genevieve in the sections examined by Ulrich, with the Aux Vases sandstone of the Mississippi Valley section wanting. The characteristic Chester fauna of the Renault limestone, mistakenly included in the Ste. Genevieve by Ulrich, led him to assign the whole of the Ste. Genevieve to the Chester. Although there is some passing of species from the Ste. Genevieve into the basal Chester, long experience in the field has demonstrated that the really characteristic Ste. Genevieve fossils species do not pass into the Renault or basal Chester, and long-continued faunal studies based upon extensive collections have shown that by far the most important faunal break in this portion of the stratigraphic sequence occurs in passing from the Ste. Genevieve limestone to the overlying Chester. This important faunal break, associated with the unconformable relation of the Chester sediments upon the underlying formations, wherever this portion of the section is exhibited, and also associated with the distinct change in sea-pattern in passing from the Ste. Genevieve to the Chester in the Illinois basin, seems to afford an abundance of evidence of various sorts for placing the major line of division within the Mississippian at the top of the Ste. Genevieve limestone. In the Mississippi River counties of Illinois this line is at the base of the Aux Vases sandstone, while in the more southern counties of the state it is at the base of the Shetlerville-Renault limestone unit. The two so constituted divisions of the Mississippian are of sufficient importance to rank as series, the Mississippian as a whole constituting a system.

[*Concluded*]

CONCERNING THE PROCESS OF THRUST FAULTING

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The following paper is offered as a contribution to the studies of low-angle faulting which have been led by the researches and teaching of Professor R. T. Chamberlin.

A comparison of this paper with previous publications, especially "Low-Angle Faulting," by R. T. Chamberlin and W. Z. Miller,[1] will show that the writer has followed Chamberlin in large measure. Most of the material here presented has really been anticipated in the article referred to, but a different manner of approach on some phases of the study is attempted, and the possibility is suggested that there may be a closer relationship between low- and high-angle thrust faults than is commonly accepted.

In 1910 Chamberlin[2] published his paper on the structure of the Appalachian Mountains in which he showed reason to believe that the part of the crust affected by deformation is a shallow, wedge-shaped mass about thirty miles deep and about nine hundred miles long. Willis,[3] upon independent but similar arguments, suggested that the depth of the mass deformed in the uplift of the Cascades lies between thirty-seven and one-half and fifteen hundred miles.

So far as the writer knows, these conclusions have been accepted as sound, in spite of the fact that they appear to be fundamentally different from the prevalent notion that mountain folding is relatively shallow and that the deformable crust of the earth is of the

[1] *Jour. Geol.*, XXVI (1918), 1–44.

[2] R. T. Chamberlin, "Appalachian Folds of Central Pennsylvania," *Jour. Geol.*, XVIII (1910), 228–51.

[3] Bailey Willis, *U.S. Geol. Surv., Prof. Paper No. 19* (1903), p. 97.

character of a thin layer or sheet. In a later paper Chamberlin[1] concludes as the result of his work in the Rocky Mountains that the western mountain mass has this generic difference from the eastern range in that it is composed of broadly folded members of very great depth as contrasted with severely folded and faulted members of less depth. Thus following Chamberlin, it seems that there are some cases of mountain folding in which the strains are relatively shallow as well as some cases in which deformation has been much deeper, which may support the theory that faulting and sharp folding may affect a shallow terrain at the same time that deeper parts of the crust are undergoing flow deformation. The observation of Daly[2] that in south central British Columbia the overlying sediments are much more sharply folded than the underlying pre-Cambrian rocks gives further support to this general notion.

In attempting to analyze earth deformation it is natural, erroneously, to consider the deformed parts of the crust as comprising the whole members subjected to stress; whereas such parts are merely those portions of the structural member which failed.[3] In consequence of this, it follows that it is a matter of considerable doubt as to what the nature and dimensions of the structual members may have been. So it comes about that most discussions are based upon an attempted analysis of the strains involved rather than upon the basis of controlling forces. And this is logical enough, in that here and there the strains remain clearly recorded, whereas the stresses and the nature of the members involved can only be inferred. Presumably, if we follow the traditional teachings, the compressive forces are caused by a more rapid decrease in volume of the inner part of the earth than can be accompanied by the solid shell without buckling or breaking, and consequently the whole shell of the earth constitutes the members concerned. However, the earth's crust is sharply divided into continental and oceanic members; whether these members are conceived to be

[1] R. T. Chamberlin, "The Building of the Colorado Rockies," *Jour. Geol.*, XXVII (1919), 248.

[2] R. A. Daly, quoted by C. K. Leith, *Structural Geology* (1913), p. 127.

[3] Cf. Chamberlin and Miller, *op. cit.*, p. 21.

segments or sectors, according to the older and the newer theories respectively, they act as individual components of a single member and as such are subject to separate analyses. Curved, rigid, sheetlike members under lateral compression fail in the center. Apparently the earth members fail by rupture and buckling at the ends or edges,[1] from which it follows, either that the conception of sheetlike members is erroneous, or that the members are not rigid bodies, or both. It is surely a fact that the earth members are not rigid under the conditions of mountain folding; the manner of their failure proves that beyond question. There is still a possibility that under some conditions the forces are transmitted through shell-like members, and that at other times the forces are distributed throughout deep earth sectors. It seems to be probable that both conditions have prevailed repeatedly at different times. Chamberlin's conclusion that the mountain ranges are of two generic types, one with deep and the other with shallow roots, supports this idea. But, however deep the strains may be, it is possible that there is so distinct a zone of shearing between the frangible, nearly rigid crust and the interior which is deformed by flow that the crustal part in any case fairly may be considered an individual member. It is probable that deep-seated strains affect a discontinuous member, plastico-rigid at depth, but more frangible toward the surface,[2] wherefore the term "plastico-frangible," perhaps, might be used to denote the characteristic quality of the outer crust. Objections to these terms arise readily, especially by comparison with the terminology of other writers. T. C. Chamberlin prefers the term "elastico-rigid"[3] because that expression indicates rigidity associated with elasticity in distinction from solidity due to high viscosity. The word "fluidable"[4] has been used to denote the potential fluidity of the earth's interior.

[1] Bailey Willis, "Mechanics of Appalachian Structure," *13th Ann. Rept. U.S. Geol. Surv.*, Part II (1893), p. 247.

[2] Cf. Bailey Willis, *U.S. Geol. Surv., Prof. Paper No. 19* (1903), p. 97, and Joseph Barrell, *Jour. Geol.*, XXIII (1915), 438.

[3] T. C. Chamberlin, *Jour. Geol.*, XXVI (1918), p. 194, and personal communications.

[4] J. W. Gregory, *Geology of Today* (London, 1915), p. 156.

But in this article there is no design either to emphasize the elasticity of the earth as a whole or the liquefaction of local parts, nor on the other hand is there any need to deny the reality of these characteristics. But inasmuch as no term has yet been devised which adequately describes the character of the earth's interior, it is necessary to choose for different purposes different terms emphasizing different phases of the earth's behavior, each admissible term being complementary and not contradictory to the others.

TERRESTRIAL FORCES AND CRUSTAL MEMBERS

The nature of earth stresses.—The usual argument is that there is a more or less rigid, plastico-frangible, unshrinking crust upon a plastico-rigid, shrinking interior. Between the central sphere and its crust, adjustment is made possible by a zone of almost no strain, above which the earth's crust must undergo strain increasing from near zero at the base to a maximum at the surface.[1] Within the zone of flow the strain is accommodated by flow, above that by a combination of flow and shearing.[2] Any thrust that may be applied in a zone of perfect flow cannot be transmitted as such; it is transmitted hydrostatically. However, it is not probable that there is a zone of perfect flow; probably the rock yields under long-continued pressure, whereas, in the manner of tar, it might rupture under a sudden shock. Such shocks are inconceivable as affecting this zone of flow, and for purposes of this discussion the zone of flow may be regarded as one in which there is a minimum of vector or directional forces. Movement of the crust over the shrinking interior would tend to produce displacement in the zone of flow at an angle approaching zero, no matter at what angle thrust forces cause rupture in the upper crust.[3]

A perfectly rigid body transmits thrust in such a way that the forces are not dissipated during transmission. This type of body does not obtain in the earth's crust, for rocks are not perfectly rigid materials. Material which is slightly plastic tends to fail near the points of the application of force instead of near the

[1] T. C. Chamberlin and R. D. Salisbury, *Geology*, II (1907), 127–30.

[2] C. K. Leith, *Structural Geology* (1913), p. 4.

[3] T. C. Chamberlin, "The Problem of Faulting," *Econ. Geol.*, II (1907), 597–99.

center, the part most susceptible in nearly rigid members. Nevertheless, the rocks within a mile of the earth's surface are, in general, more nearly rigid in behavior than those near the zone of flow. Furthermore, there is more force to be transmitted presumably near the surface, because the length of the arc is greater at the surface than near the center, and the accumulative forces are proportional to the length of the arc to be accommodated to the shrinking. Consequently, there is a greater thrust transmitted in the rocks near the surface than through those near the zone of flow for two reasons, because the rocks are more nearly rigid, transmitting a greater proportion of the forces extant, and because near the surface there is more total horizontal force to be transmitted. These conditions may be analyzed as an unequally distributed force of the rotational type. Since the strain is greatest where relief of pressure is easiest, it follows that the strain is greater near the surface than at depth, which would result in a rotational strain even if the forces were translatory.[1] Thus rotational strain results from a ready relief of pressure near the surface, and it appears reasonable that the original stresses applied also are rotational.

The length of the crustal members.—The commonly deformable crust is considered to be a discontinuous structure in the form of a supported hollow sphere composed of irregularly shaped, curved strata plates which are geographically coincident with the continental and oceanic segments. These members of the structure exert thrust forces on one another which are localized in their maximum application at the planes of contact, i.e., the borderland of continents and oceans. Roughly speaking, the members involved in the compression are as long as the continents and ocean basins are wide. The forces, however, are not of equal intensity everywhere along the length of each member; under normal conditions they are least in the center and greatest at the ends. If the earth's crust were truly rigid the intensity of thrust would be equal throughout the length of each member, each segment would serve as a footing for its neighboring segments, resulting in failure of the segments near their centers. Apparently the

[1] F. D. Adams and J. A. Bancroft, *Jour. Geol.*, XXV (1917), 637; R. T. Chamberlin and W. Z. Miller, *ibid.*, XXVI (1918), 35–37.

members fail near their ends probably due to the fact that forces are not transmitted well through partly deformable members. The condition of a single member may be represented as in Figure 1, in which it is indicated that the thrust decreases from a maximum at the edges of the continental and oceanic segments to a minimum near their centers. Part of the force is absorbed in minor deformation of the member and only part is transmitted; therefore, the increase of force toward the end of the members is not one of arithmetical progression. Thus the yielding of the earth's crust permits the stresses relief, so that at one time the intensity of

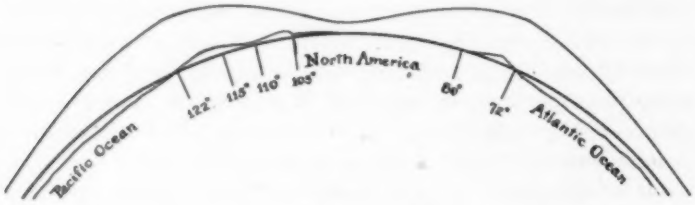

FIG. 1.—Diagram to illustrate the supposed distribution of transmitted crustal stresses. The top line is supposed to represent graphically the magnitude of the transmitted stresses. The transmitted stresses vary from a minimum near the centers of the oceanic and continental segments to zones of maximum intensity near the borders of the continents.

thrust on one side of a yielding section is much greater than the intensity of thrust on the other side of the yielding section. This condition results in a movement of part of the member in the direction of the lower intensity of thrust. This direction of movement is commonly said to be the direction of the deforming force. However, action and reaction being equal and opposite, the direction of any force must be two-faced. But whatever the direction of movement, either toward or from the continental masses, the continental masses exert just as great a thrust upon the oceanic masses as they bear themselves. Consequently there must be a tendency for the oceanic masses to suffer deformation, especially near the continents. There is supposed to be a region or band of great stress at the borders both of oceanic and continental masses, within which major deformation should be expected.

Let it be noted, however, that this band of great stress is supposed to be but a part of the total member under compression.

The depth of the crustal members.—According to Chamberlin and Salisbury[1] (writing in 1904) the average thickness of the folded shell is probably between three and five miles. From the context it appears that the estimate was based, in part at least, upon a reconnaissance report on the amount of uplift and shortening involved in the Appalachian folding, and the resulting figure probably should be modified especially by the results of R. T. Chamberlin before quoted, as well as by the many contributions based upon experiments made since 1904. Heim concludes from his studies in the Alps that there the great deformations were relatively shallow in extent. In 1912 F. D. Adams reported that open cavities might persist in rocks at depths of at least eleven miles,[2] from which it appears that the zone subject to fracture and flow, or plastico-frangible deformation, might be deeper than usually expected. But from his work in association with Bancroft,[3] Adams finds that the amount of thrust required to produce deformation increases rapidly with the increase in depth, and therefore concludes that the transference of material at the earth's crust must take place comparatively near the surface. Bridgman,[4] who subjected metal pieces to pressures comparable to those that are supposed to obtain at depths of between twenty and seventy miles, agrees that substances tend to become more rigid under high pressures, but reports further that under great pressures there is no relation between the yield and rupture points, for there is no rupture point. Materials (metals at least) deform without rupture, although they remain highly rigid. This is the condition supposed to be characteristic of the great interior of the earth, which is therefore called plastico-rigid.[5]

[1] *Op. cit.*, p. 126; cf. Bailey Willis, *U.S. Geol. Surv., 13th Ann. Rept.*, Part II (1891–92), p. 228.

[2] F. D. Adams, *Jour. Geol.*, XX (1912), 97–118.

[3] Frank D. Adams and Austin J. Bancroft, *ibid.*, XXV (1917), 635.

[4] P. W. Bridgman, *Phil. Mag.* (July 1912), p. 65; see also *Phys. Review*, XXXIV (1912), 1–24.

[5] A later paper by Bridgman has further bearing on the probable plastico-rigid behavior of the interior, "On the Effect of General Mechanical Stress on the Temperature of Transition of Two Phases, with a Discussion of Plasticity," *Phys. Review*, New Series, VII (1916), 215–23. See also Joseph Barrell, *op. cit.*, pp. 431–32.

All these researches seem to indicate that the zone of fracture, folding, and of deformation in general which may be called plastico-frangible is probably confined to depths which properly may be called shallow.

T. Mellard Reade[1] used the terms sheet or strata-plate to describe the deformable parts of the earth's crust, and Chamberlin and Miller[2] suggest that the deformation of some folded mountain chains is perhaps analogous to the deformation of a thin prism or wall.

Probably few geologists would maintain that the frangible part of the earth's crust is more than fifteen miles deep.

The probability of crustal members as such.—Thus, the crustal members are conceived to be sheets conforming to the curvature of the earth, from 200 to 300 times as wide and long as they are thick. Their proportions may be compared to those of a pavement one foot thick covering a city block about three hundred feet square. This conception of strata-plate members of great length and width might appear unreasonable were it not for the fact that each member is not an unsupported arch. Each member is very appreciably stiffened by the support of the plastico-rigid or elastico-rigid mass beneath.

A consideration of the probable effects of the yielding of such members is interesting. Supposing that there should be mountain folding near the border of a continent, the yielding decreases the stresses at the place of failure and throughout a certain distance on either side. Were the crust rigid instead of plastico-frangible, the stresses would be relieved throughout the whole of the neighboring sections, and the stress relief would be distributed promptly throughout all the members of the earth's crust. Thus, distribution of relief would tend to become world-wide, but the plastic-like behavior of the members retards such a distribution of stress and in some cases absorbs it within a relatively short distance. In such cases conditions for the continental mass may include a relieved, small, residual stress on one side of the continent and a large, almost unrelieved stress on the other side of the continent. This may result in a later break on the unrelieved

[1] T. Mellard Reade, *The Evolution of Earth Structure* (1903), p. 134.

[2] *Op. cit.*, p. 21.

side of the continent or may give rise to further slow adjustments affecting the major part of the continental member. In short, the mutual bearing of the crustal members upon one another may be partly responsible for the usual, very widespread epirogenic movements which follow mountain folding. These conceptions may appear at first glance to be clearly reactionary and out of accordance with modern views based on the research and studies of the last twenty years, especially with the conceptions of T. C. Chamberlin,[1] who discusses deep, rigid earth cones separated from one another by shear zones, but so far as is known to the writer these ideas are not necessarily in conflict with such conceptions of the earth's interior. It should be emphasized that the writer's suggestions are based on the assumption, which seems to be widely accepted, that there is a crustal member, subject to fracture and flow, separated from the underlying plastico-rigid interior by a zone of shearing or flow. The recognition of this zone of separation causing the crust and the inner mass at certain times to be a discontinuous member, the parts of which are subject to separate analysis, is absolutely fundamental to this discussion. It may be that this zone of shearing is merely an occasional phenomenon coming into being only as the result of more fundamental processes, and that its depth (and in consequence its competence) may vary from time to time with different periods of stress, and it is likely that the development of such a zone to an extent comparable with the width of a continent is an extreme and unusual condition. And it must be recognized that the writer advances this study as a contribution to the analysis of low-angle faulting, in its proper relation to the other factors listed by Chamberlin and Miller[2] in the résumé of their paper previously quoted, with this difference, arising largely from the different manner of approach, that the writer would not list "length of deformed area with respect to its other dimensions (after analogy of long column)" among the minor factors, but rather among the major factors in low-angle faulting. Nevertheless, it is held to be but one of several major factors. The revision

[1] *The Origin of the Earth* (1916), chap. viii, and *Jour. Geol.*, XXVI (1918), 197.

[2] *Jour. Geol.*, XXVI (1918), 44.

of the proportions of the crustal units, the abandonment of any idea of those members being unsupported arches, the recognition that they are probably relatively temporary phenomena coming into being only upon occasion, and the limitation of this discussion to those members subject to fracture put this conception of strata-plate members in an entirely different class from the old theory of crustal members which Chamberlin and Salisbury[1] emphatically discarded long ago.

A comparison of the crustal members with sheets and long columns.—Euler's formula[2] has been used in comparing the deformation of sheetlike members of the earth's crust to the yielding and failure of long columns because the failure of sheets is similar to that of long columns and because analyses of the deformation of sheets under lateral thrust are rare or wanting. Euler's formula applies strictly only to columns having lengths many times greater than their least diameter. Of course this formula is used merely as an illustration of the order of magnitude of the strength of a sheet. It is not accurate to apply it even to every long column; yet it applies with appropriate empirical modifications to all long columns.

W. H. Burr[3] says: "Pieces of material subjected to compression are divided into two general classes—'short blocks' and 'long columns'; the first of these only, afford phenomena of pure compression. A 'short column' is such a piece of material, that if it be subjected to compressive load it will fail by pure compression. On the other hand, a long column (as has been indicated in Art. 25) fails by combined compression and bending. . . . . The length of a short block is usually about three times its least lateral dimension."

Therefore it is concluded that the earth's crust in major deformation follows closely the behavior of long columns because it

[1] T. C. Chamberlin and R. D. Salisbury, *Geology*, I (1904), 554–62.

[2] T. T. Quirke, *Geol. Survey, Canada, Mem. No. 102*, "Espanola District, Ontario" (1917), p. 71, and Chamberlin and Miller, *op. cit.*, p. 19. According to Euler's formula the strength of a column equals

$$EI\frac{\pi^2}{L^2},$$

in which E equals the coefficient of elasticity of the material involved, I equals the moment of inertia, and L equals the length of the column.

[3] W. H. Burr, *The Elasticity and Resistance of the Materials of Engineering* (1890), p. 371.

appears to yield first by flexure and then by rupture, and that many experiments performed by Willis, Cadell, Chamberlin, Miller, and others, technically speaking, are experiments with long columns rather than with short blocks, because the members flexed before rupturing. More strictly speaking, most of these experiments on deformable materials fall under the mechanical analyses of neither short blocks nor of long columns because of the nature of the material, but they seem to accord the more closely to long-column analysis. If an adequate amount of experimental and analytical work had been done upon the deformation of sheets,[1] the writer would have used only the sheet as an illustration of earth deformation.

THE RUPTURE OF SHEETS AND LONG COLUMNS

Experiments with sheets under rotational stress.—In hope of learning more about the deformation and rupture of sheets the writer performed a few simple experiments upon easily controlled members. T. Mellard Reade has done sufficient work with straight and circumferential compression upon sheets, but the effects of a vertically unequally distributed stress heretofore have not been tried. Reade[2] draws conclusions from the deformation of the lead lining of a scullery sink. The writer used a common bench vise to deform and rupture plates of soap and paraffin. Of the two, soap was the more satisfactory. In order to secure an unequally distributed stress a wedge was inserted, large end upward, between the end of the member and the face of the vise. This resulted in bringing greater pressure to bear near the top than near the bottom of the plate. If the plate had been quite free to bend it would have bent downward; however, that would not have illustrated the deformation of rock strata, and the member was therefore stiffened enough by slight pressure from below to make it bend upward. After the bending of the soap, rupture started from the bottom at a low angle from a point nearly equidistant from each

[1] The only work known to the writer which appears to have a bearing on the subject is "Tests of Reinforced Concrete Flat Slab Structures," by Arthur N. Talbot and Willis A. Slater, *University of Illinois Bull.*, Vol. XIII, No. 22, 1916.

[2] T. Mellard Reade, *The Origin of Mountain Ranges* (1886), pp. 15–16, and Plate VI, p. 28.

side, became nearly horizontal near the center, and increased to nearly 60° as it approached the upper surface (Fig. 2). To prove that this is the usual type of break and not fortuitous, two more pieces of soap were flexed and broken with similar results. Two narrow pieces of soap broke with nearly vertical shear planes near

FIG. 2.—(*a*) A sheet of soap ruptured by combined compression and bending under rotational stress. The fault plane is high-angled near the surface and low-angled below the center of the member. These pieces are outlined in Figure 3. (*b*) A sheet of paraffin ruptured by combined compression and bending under rotational stress. The fault plane is almost horizontal for most of the length, changing sharply at a high angle to the surface. At one end the member is split down the center along the plane of maximum shear without actual breaking out of the piece; see also Figure 5, (*a*) and (*b*).

the edges (Figs. 2 and 3), but a plate wider than it is long ruptured without vertical shear planes at a low angle (Fig. 4). It seems that nearly vertical fault planes may be disregarded, occurring merely because the sheets are narrow and have lateral relief. In the case of earth deformations in general, the width of the sheet or strata-plate is probably comparable to the length of the defor-

mation member, and vertical fault planes of a comparable origin are not commonly recognized.

Experiments with short blocks under rotational stress.—Experiments with paraffin led to somewhat different results. The

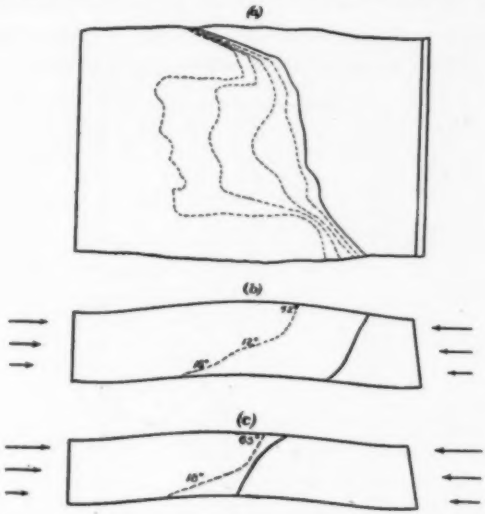

FIG. 3.—(*a*) and (*b*) are two views of a sheet of soap which failed by combined compression and bending under rotational stress. The dimensions of the piece of soap are $\frac{5}{16} \times 4\frac{1}{2} \times 2\frac{1}{2}$ inches. The contour intervals are $\frac{5}{16}$ inch, indicating the plane of rupture. A photograph of the piece is reproduced in Figure 2. (*c*) is a cross-section of another piece of soap showing a similar rupture. The dimensions are $\frac{7}{16} \times 4\frac{5}{16} \times 2\frac{5}{16}$ inches.

paraffin members did not flex so readily as soap, and therefore, in spite of their dimensions, they approach the behavior of short blocks under the conditions of these experiments. The members did not break from the bottom to top but after a few preliminary high-angle slice faults part of the members seemed to chip out (Fig. 5, *c* and *d*), illustrating the manner in which weak unbending blocks yield under a rotational compression.[1] However, having

[1] In experimental engineering any cement block which is loaded with an unequally distributed load fails by breaks, making low angles with the direction of applied force. Such breaks are considered faulty, because the object of that work is to determine the strength of the blocks under equally distributed stress.

flexed slightly, one paraffin member started to split down the center along a plane parallel to the surface in the manner of a bending column (Figs. 5 and 2).

Chamberlin and Miller[1] had obtained similar low-angle breaks when they caused rotational strain in a paraffin short block, thereby proving their contention in favor of the importance of rotational strain as a cause of low-angle faulting. The writer

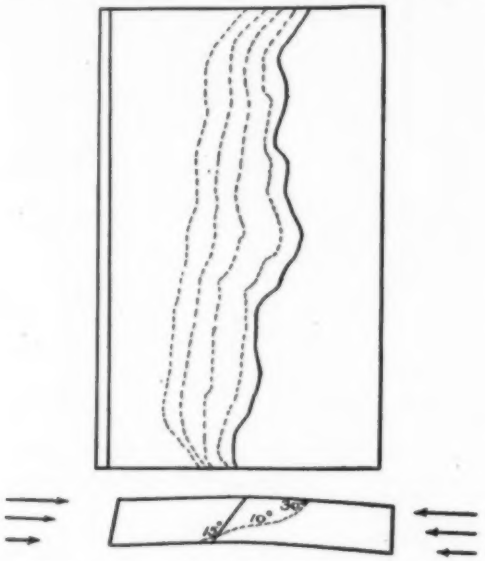

FIG. 4.—A wide sheet of soap which failed under rotational stress by combined compression and bending. The dimensions of this piece are $2\frac{4}{10} \times 4 \times 1\frac{4}{10}$ inches and the contour lines are equidistant. They indicate the place of rupture.

has used a rotational stress and bending sheets rather than short blocks in order to be consistent in the general treatment and object of the paper and for the sake of the mechanical considerations which are treated later.

Analysis of the rupture of sheets and columns under translatory forces.—Long columns and sheets fail by bending and by rupture

[1] *Jour. Geol.*, XXVI (1918), 35, and Fig. 16.

under continued compression. A column may crumple into many folds or it may spring out into a single arch. The second case is stable for unsupported columns, but in the case of the earth's crust the formation of many folds is common. Mechanically the analysis of the stresses in one fold of a series is the same as that in a single arch. The maximum tensional stress is at the apex of the

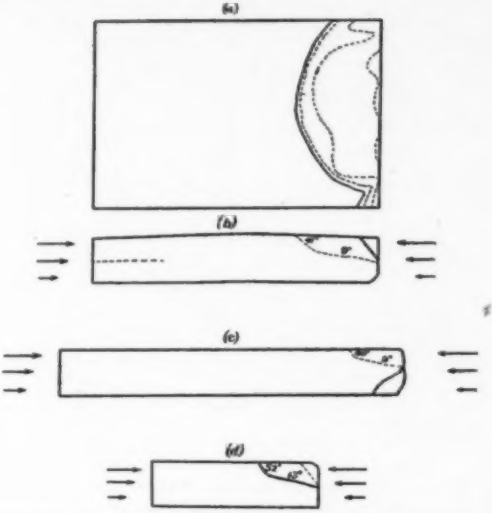

FIG. 5.—Paraffin members which failed under rotational stress. (*a*) and (*b*) are two views of a piece $\frac{8}{10} \times 3\frac{8}{10} \times 2\frac{4}{10}$ inches in size, which yielded by combined compression and bending. Compare Figure 2 and note the place of rupture along the plane of maximum shear parallel to the surface. (*c*) is a side view of a piece $\frac{8}{10} \times 4\frac{8}{10} \times 2\frac{4}{10}$ inches which seemed to fail by mere compression; the break indicated by dotted lines followed several high-angle breaks. (*d*) is a side view of a piece $\frac{8}{10} \times 2\frac{8}{10} \times 2\frac{4}{10}$ inches in size which ruptured without flexing. Note the tendency toward high-angle breaks.

arch at the surface, the maximum compression beneath the apex of the arch at the bottom of the deformed member, the focus of maximum shear a plane containing the axis of the member and parallel to the plane of greatest length and width of the member (Fig. 6*B*, *S–S*). A bending member which yields to shear alone splits from end to end along a plane of maximum shear, a similar

member yielding to tension parts in a plane at right angles to its axis. Figure 7 illustrates the rupture of flexed wooden columns by tension and shear. Examples *A* and *B* have ruptured by tension and by shear, whereas example *C* has ruptured by a combination of tension and shear. Applying these illustrations to conditions in the earth's crust, it is probable that rock is so weak to resist tension that under continued straight compression its folds are likely to rupture at the arches by tension. In the case

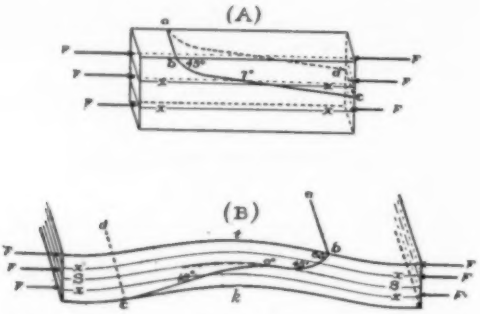

FIG. 6.—*A* illustrates the character of rupture of a short block under highly rotational compression. The surface *abcd* represents the break. The planes marked *x* represent the distributed shear due to the unequally distributed forces *F*. *B* illustrates the character of rupture of a long column or of a flexible sheet by rotational compression. The plane marked *S* is the plane of maximum shear due to flexure; the planes marked *x* indicate the planes of distributed shear and the action of the unequally distributed forces *F*. The place of maximum tension is marked *t* and the place of maximum compression is marked *k*. The rupture *abcd* ideally follows the plane *S*–*S* partly and emerges near *t*.

of major terrestrial deformations, however, straight compression is thought to give place to rotational forces, and the situation is changed.

Analysis of the rupture of sheets and columns under rotational forces.—Any compressive force unequally distributed in its application gives rise to shearing stresses within the member affected. The case of members folded by rotational forces includes tension due to bending, shear due to bending, and shear due to rotational stress. The plane of maximum shear is somewhere near the middle

of the member (Fig. 6), and the tendency to shear due to rotational stress is distributed in parallel planes, one of which must coincide with the plane of maximum shear due to folding. Thus rotational stress adds a tendency to shear along the plane of maximum shear already developed by folding. This explains the low-angle breaks

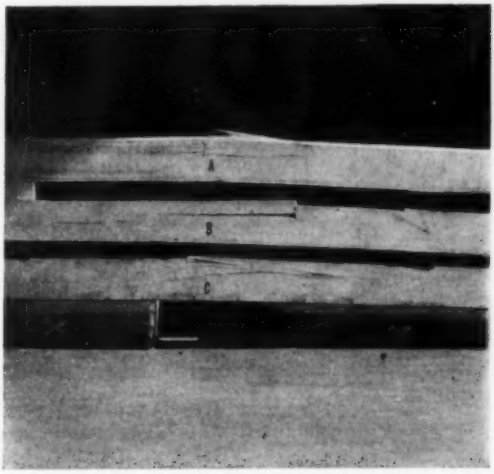

FIG. 7.—The rupture of flexed wooden columns by tension and shear. Under flexure, columns tend to split from end to end due to shearing, and to part in a plane at right angles to their long axes above the plane of shear by tension. Tension is greatest at the top of the arch, and shear is greatest along the center of the member. *A* and *B* show separate breaks due to shear and tension and *C* shows rupture induced by a combination of shear and tension.

near the center of the slightly flexed paraffin sheet (Figs. 2 and 5), and the suggestion of a very low-angle break near the center of the ruptured soap (Figs. 2 and 4).

Contemporaneous with this tendency to shear along a plane parallel to the axis of the deformed member, there is a lesser tendency to rupture by tension. The tensional break approaches a plane normal to the top of the arch, at right angles to the plane of maximum shear (Figs. 6 and 7*A* and *B*). A combination of these two is a plane which sweeps through a considerable change of

position amounting to 90° in extreme cases. Such a combination is illustrated in the breaking of one wooden piece (Fig. 7*C*) and in the rupture of the soap and paraffin (Figs. 2, 3, 4, and 5).

Comparisons between geological thrust deformations and members ruptured by rotational stress.—In cases where rock members are subjected to both tension and shear we expect failure to be due to that which the rock is least able to withstand, that is, a combination of both shear and tension. Rocks are strong to resist compression, and failure of rock members by straight compression needs little consideration when either great shear or great tension is involved.

Comparisons between the rupture of these members which fail by combined compression and bending, the rupture of short blocks which fail by pure compression, and the geological relations of overthrust and reverse faults seem to suggest that many thrust faults may have resulted from the yielding of flexed members which have failed along planes of shear and tension, members of the class of long columns.

Thus it appears that some members under terrestrial compression are curved sheets or strata-plates, which are thin in comparison with their width and length; being subjected to an unequally distributed rotational stress they break normally along shear planes of low angles at depths which steepen to high angles due to tension near the surface.

KINETICS OF THRUST FAULTING

Analysis of the conditions following rupture and preceding displacement.—Some rotational force deforms the terrain by flexure. If the folding is sharp no fold can transmit thrust because the fold must fail at the crown of the arch due to localized tension. Rock is incompetent to carry tensional stresses, and therefore a high arch fails under lateral compression. If the arch fails, no appreciable thrust can be transmitted until folding has reached an isoclinal condition, involving great shortening, great thickening, and thereby great strengthening of the member.[1] This case is extreme and must be rare. More commonly the folds are so low that thrust

[1] Cf. Quirke, *op. cit.*, p. 72.

can be transmitted without rupture of the arches, and rupture follows the forms outlined above (Fig. 6). In an analysis of the conditions at the instant after rupture, let P be the total compressive force, let G be the weight of the moving mass, let Θ be the angle of shearing at any one place, and let a represent the cross-sectional area of the member. Then, as Chamberlin and Miller show,[1] the intensity of thrust (p_t) tangential to the shear plane is

$$p_t=\frac{P\sin\Theta\cos\Theta}{a}$$

and the intensity of the normal stress (p_n) is

$$p_n=\frac{P\sin^2\Theta}{a}$$

Likewise, the force of gravity is resolved into tangential and normal components, the tangential opposing the tangential component of the thrust, and the normal being added to the normal component of the thrust. The tangential component of gravity is

$$G_t=G\,x\sin\Theta,$$

and the normal component is

$$G_n=G\,x\cos\Theta.$$

The intensity of the tangential component of gravity is

$$g_t=\frac{G\sin\Theta}{a\cot\Theta}=\frac{G}{a}\sin\Theta\tan\Theta.$$

The intensity of the normal component of gravity is

$$g_n=\frac{G\cos\Theta}{a\cot\Theta}=\frac{G}{a}\sin\Theta.$$

Thus, after rupture the intensity of thrust becomes

$$\frac{P\sin\Theta\cos\Theta}{a}-\frac{G\sin\Theta\tan\Theta}{a}=\frac{\sin\Theta}{a}\,(P\cos\Theta-G\tan\Theta),$$

and the intensity of friction becomes

$$\mu\left(\frac{P\sin^2\Theta}{a}+\frac{G}{a}\sin\Theta\right)=\mu\,\frac{\sin\Theta}{a}(P\sin\Theta+G),$$

in which μ represents the coefficient of kinetic friction.

[1] *Jour. Geol.*, XXVI (1918), 15 ff.

In order to achieve displacement,

$$\frac{P \sin \Theta \cos \Theta}{a}$$

must be sufficiently greater than

$$\frac{G \sin \Theta \tan \Theta}{a}$$

to overcome the friction due to both the normal component of thrust and the normal component of gravity. The friction will become less per square unit of fault plane as slickensides and other smooth surfaces are developed by movement. But the total area of friction increases with displacement, and it follows from the preceding formulas that friction is greatest in intensity where Θ, the angle of displacement, is greatest.

The fault plane decreases in steepness as displacement increases.—Rupture being accomplished, as indicated in Figure 6*B*, the fault plane varies from places of low dip far beneath the surface to places of high dip nearer the surface. Where the angle is low the tangential thrust is greatest, the normal component of thrust is least, but the normal component of gravity is a maximum, and the resistant, tangential component of gravity is a minimum. Near the surface where the angles are high and the normal component of gravity is low, the resistant tangential thrust due to gravity is a maximum and the tangential component of the compressive force is a minimum, but its frictional component is a maximum. In all these movements the compressive thrusts must be dominant, otherwise the force of gravity and friction would prevent displacement. Therefore, displacement being granted, the effect of gravity is not vital in the discussion. Obviously, then, the effects of thrust result in a maximum shear along low-angled planes and a maximum friction at high-angled planes.

In the general case of rupture represented in Figure 6*B* maximum friction is near the surface. The hanging wall of millions of tons of rock moving several miles along this fault plane will result in enormous abrasion, much as a glacier abrades greatly the stoss sides of steep opposing hillsides, and this abrasion will be greatest

where friction is greatest, at the steepest part of the plane, affecting both the footwall and the hanging wall. During early displacement the fault will appear at the surface as a steeply dipping plane; by the time displacement has continued for a mile, the angle of the fault plane must have been worn flatter by the friction of the moving load; finally, by the time displacement has attained a few miles, the low-angled sole will have reached the surface, and the fault plane must have been reduced to a low angle by abrasion, leaving no trace of the steep parts of the original break.

In this manner it is suggested that all great thrust faults which are steep-angled near the surface, if persistent in depth, follow the low-angle form at the depth of a few miles, and that in a general case the angle of faulting at the surface may depend as much upon the amount of displacement subsequent to rupture as upon fundamentally different conditions in the application of earth forces or in the character of the members affected. In support of this it may be recalled that, so far as is known regarding thrust faults, all faults of great displacement have low-angle fault planes, and no faults of high angles exceed a few miles in displacement.

Willis[1] has described rotated, high-angle thrust faults of relatively small throw in the coast ranges and the Sierra Nevada, which he considers to have some such shape as is here suggested for thrust faults of small displacement; however, his explanation of their character differs considerably from the general argument of this paper.

CONCLUSION

In conclusion some repetitions seem pertinent. Certain parts of the earth's crust which are deformed by regional compression are held to be analogous to sheets and comparable in mechanical analysis to long columns. The normal terrestrial stress is said to be an unequally distributed thrust of rotational type. The transmission of stress as a vector quantity supposedly extends from the surface to a depth scarcely exceeding fifteen miles. There is a zone of potential separation between the frangible crust and the rigid interior which is nearly parallel to the surface. In some cases thrust faults of very great displacement may be extensions

[1] Bailey Willis, *Geol. Soc. Amer. Bull.*, XXX (1919), 84–86.

of this low-angle zone of parting to the surface at an increasing degree of steepness;[1] in other cases rupture occurs within the bending part of the crust near the plane of maximum shear with a break low-angled at depth and increasing in steepness near the surface. In either case displacement of less than one mile results in a steep-angle fault, an ordinary reverse fault, but displacement of several miles results in reduction of steepness of the fault plane by the abrasion of the footwall and by advancement of the low-angle part of the hanging wall to the surface. Thus some low-angle overthrust faults and high-angle reverse faults may represent different stages of a single process.

[1] T. C. Chamberlin, *Econ. Geol.*, II (1907), 597–99.

PLEISTOCENE MOLLUSCA FROM INDIANA AND OHIO[1]

FRANK COLLINS BAKER
Curator, Museum of Natural History, University of Illinois

Two very interesting and valuable collections of Pleistocene material have recently been placed in the hands of the writer for study. These contain a number of species not previously reported from fossiliferous beds, which add largely to our knowledge of the distribution of this group of animals during the great Ice Age. These deposits will be discussed separately and their biotic content compared.

I am indebted to Dr. Morris M. Leighton, of the department of geology, University of Illinois, for the opportunity of studying the Ohio deposit, and to Rev. W. H. Fluck, of Hope, Indiana, for the material from the Indiana deposit. The following gentlemen have examined critical material and to them my thanks are due: Dr. H. A. Pilsbry, Academy of Natural Sciences, Philadelphia, Amnicolidae; Dr. V. Sterki, New Philadelphia, Ohio, Sphaeriidae; Dr. Bryant Walker, Detroit, Michigan, Amnicolidae and Physa; and Mr. Calvin Goodrich, Pleuroceridae.

THE OHIO DEPOSIT

The material from Ohio occurs in extensive marl beds at the south end of Rush Lake, Logan County. Dr. M. M. Leighton, who collected the material, thus describes the deposit:

> The exposure occurs in an artificial ditch which drains into the lake from the south. The beds begin close to the lake and run south for a hundred yards or more. The farm land immediately to the east shows great numbers of these shells mixed in with the soil. The exposure is about six feet deep, and the shells make up whole beds of lenticular shape, interbedded with clay strata, in some of which are a few scattered shells. Some of the shell beds are as much as ten inches thick. The interbedded clay shows no lamination and is dark in color. I do not believe there is any question about their being post-Wisconsin in age, but on the other hand they do not seem to be extremely recent.

[1] *Contribution from the Museum of Natural History*, University of Illinois, No. 9.

Logan County is within the late Wisconsin drift border and the fauna is without question of post-Wisconsin age.

The fauna of the Ohio deposit contains several species of unusual interest. A new variety of *Amnicola* is related to a recent species described from Maine—*Amnicola winkleyi leightoni*. The two forms are widely separated geographically, but the relationship seems unquestionable. It is probable that this variety, as well as the typical form, occur in other places between the two localities, but have not yet been recognized. All of the large Amnicolas have generally been identified as "*limosa*" and many of the more recently described species and races of this and other groups will be found in other Pleistocene deposits when these are critically examined. *Physa anatina* is the most easterly record for this species which is abundant, living, west of the Mississippi River, and also more or less common in Illinois and Michigan. This is the first record of this *Physa* in Pleistocene deposits of the glaciated regions. The recently described *Planorbis altissimus*, first noted in a marl deposit in Illinois, occurs in abundance in the Ohio deposit. This small *Planorbis* is believed to have a wide distribution in the eastern and central parts of the United States in Pleistocene formations. It may also occur living. The number of species and varieties of the genera *Valvata*, *Amnicola*, and *Planorbis* in this deposit is also noteworthy.

It will be observed that in the Ohio deposit there are no land shells and only one naiad species, an *Anodonta*, a genus characteristic of quiet bodies of water like lakes and ponds. The *Sphaerium* is a species commonly found in lakes. The other genera present, particularly *Valvata* and *Planorbis*, contain species that usually have a wide distribution in lakes. The Ohio deposit may, therefore, be considered as having lived in a larger Rush Lake, perhaps not long after the ice had disappeared from Ohio.

The Indiana deposit contains many land shells and six species of naiads, characteristic of rivers and streams. *Sphaerium* and *Pisidium* are largely represented, as is also the family Amnicolidae. The presence of *Goniobasis semicarinata* also stamps this deposit as fluviatile in character, as distinguished from the Ohio deposit,

which is lacustrine. The family relationship as regards number of species represented in the two deposits is shown in Table I.

TABLE I

COMPARISON OF FAMILIES IN OHIO AND INDIANA DEPOSITS

	Ohio Lake Deposit	Indiana River Deposit
Unionidae	1	6
Sphaeriidae	8	12
Valvatidae	4	1
Amnicolidae	3	7
Pleuroceridae	.....	1
Viviparidae	.....	1
Ancylidae	1	1
Physidae	1	1
Planorbidae	7	2
Lymnaeidae	2	1
Total number of species	27	33

The species of the two deposits are shown in Table II, in which the particular species in each family are listed. It will be noted that there are twenty-seven species and races in the Ohio deposit and thirty-three species and races in the Indiana deposit.

TABLE II

COMPARISON OF FOSSIL FAUNAS

Ohio	Indiana
.....	*Lampsilis ventricosa*
.....	*Amblema undulata*
.....	*Carunculina glans*
.....	*Elliptio crassidens*
.....	*Elliptio gibbosus*
.....	*Actinonaias ellipsiformis*
Anodonta species	.....
.....	*Sphaerium solidulum*
.....	*Sphaerium stamineum*
.....	*Sphaerium striatinum*
.....	*Sphaerium fabale*
Sphaerium sulcatum	.....
Musculium rosaceum	.....
.....	*Pisidium virginicum*

TABLE II—*Continued*

COMPARISON OF FOSSIL FAUNAS

Ohio	Indiana
Pisidium compressum, var.	*Pisidium compressum*
.....	*Pisidium cruciatum*
.....	*Pisidium kirklandi*
.....	*Pisidium fallax*
Pisidium pauperculum	*Pisidium pauperculum*
Pisidium noveboracense	*Pisidium noveboracense*
.....	*Pisidium abditum*
Pisidium variabile	.....
Pisidium tenuissimum	.....
Pisidium medianum	.....
Valvata tricarinata	*Valvata tricarinata*
Valvata tricarinata perconfusa	.....
Valvata tricarinata unicarinata	.....
Valvata sincera	.....
Amnicola walkeri	*Amnicola walkeri*
Amnicola lustrica, var.	.....
.....	*Amnicola lustrica*
.....	*Amnicola limosa parva*
Amnicola winkleyi leightoni	.....
.....	*Pyrgulopsis sheldoni*
.....	*Somatogyrus depressus*
.....	*Pomatiopsis lapidaria*
.....	*Pomatiopsis cincinnatiensis*
.....	*Goniobasis semicarinata*
.....	*Campeloma integrum obesum*
Ferrissia parallela	.....
.....	*Ferrissia rivularis*
Physa anatina	.....
.....	*Physa crandalli*
Planorbis campanulatus	.....
Planorbis antrosus	*Planorbis antrosus*
Planorbis antrosus striatus	.....
Planorbis altissimus	.....
.....	*Planorbis parvus*
Planorbis deflectus	.....
Planorbis hirsutus	.....
Planorbis exacuous	.....
Galba palustris	.....
Galba obrussa decampi	.....
.....	*Galba humilis modicella*

THE INDIANA DEPOSIT

The material from Indiana is from Flat Rock River, German Township, Bartholomew County. The deposit was discovered and has been studied quite extensively by Rev. W. H. Fluck, of Hope, Indiana, to whom I am indebted for the opportunity of working up this very interesting lot of mollusks.

Mr. Fluck writes as follows of the deposit and the territory immediately surrounding this place:

> On the surface, everywhere, we have glacial deposits in the form of clay, sand, gravel, and loam. The Illinoian moraine and the Shelbyville moraine are both south of these shell deposits. To the north are other moraines. In fact, the Flat Rock River flows a part of its course between moraines, to the north and east of the "Bartholomew Deposits," as I call the shell place. The top stratum, a sandy loam, in which the shells are found, is from two to twelve or more feet deep. Below this there is good gravel and sand. The river banks are twelve to fifteen feet high. On the east side of the river there is an open gravel bed where I also took shells. The shells range from just beneath the soil to as far down as I could examine, that is, down to the river surface, and, I suspect, down to the Devonian rock, over which the glacial deposits now lie. To be clear, on the east and west side of the river, and all along for several miles, below the Wisconsin drift, the shells are found. I have not explored north of this. On the west side, the shells come from a steep bank in which the shells are imbedded at all depths. On the east side, at about twenty-five yards back from the bank, I took some from an open gravel bed, not out of the gravel, but from the sandy loam above the gravel. The sample of soil and shells I am sending you came from the west bank, at about twelve feet below the surface.

The shells in the deposit seem referable to the Sangamon interglacial interval. The deposits of sand, sandy loam, and gravel are in valleys that were used as lines of drainage from the early and late Wisconsin ice sheets (see Leverett, 1902, Pl. II). The Illinoian till is only four or five miles west of Flat Rock River and the material in the stream valleys appears to be outwash or drainage material from the later ice sheets. Of the Sangamon interval in Indiana, Leverett says:

> The Sangamon soil and weathered zone may be seen beneath the surface silt in thousands of exposures in southeastern Indiana and southwestern Ohio, for the general thickness of the soil is only four or five feet. Farther north

there are, in addition to the silt, the heavy deposits of Wisconsin drift, which have buried the soil and weathered zone to such a depth that it is rarely exposed. However, a few exposures have been found in the deeper valleys, and wells not infrequently penetrate both the silt and soil under the Wisconsin drift (1902, p. 292).

On another page the same author says:

In fact, the great majority of buried soils reported in Ohio, Indiana, and Illinois appear to be at this horizon (p. 293).

The shells in the deposit under discussion are not from one of these old soil horizons. They represent, probably, material that was washed down from flood plains farther upstream, where they had been deposited during periods of flood previous to the advance of the Wisconsin ice cap. The fact that the shells are found from just beneath the surface to the lowest strata accessible, as described by Mr. Fluck, indicates that the burying of the shells occurred more or less continuously during the deposition of the valley deposit.

What relation the Peorian interval may bear to these shells is not at present known, the Iowan invasion apparently not notably affecting this territory so far east of the area of this drift. The mollusks might have lived during Peorian time and then been buried by the Wisconsin deposits. As the land fauna is so nearly like that of deposits farther south, which are referred to the Sangamon interval by Leverett, it seems best to refer the Flat Rock shells to the same horizon. At Lawrenceburg, near the Ohio-Indiana line, old soils (forest beds) containing shells are found. Some years ago Mr. A. C. Billups (1902, p. 50) listed many species of land mollusks from the deposits along the Ohio River near Lawrenceburg. These are listed in Table III for comparison with the Flat Rock shells, which are also shown in this table. It will be noted that the two faunas are substantially the same. The difference is only what we would find in comparing the recent faunas of two more or less widely separated areas. It would appear, therefore, that the reference of the Flat Rock River shells to the Sangamon interval is well supported by the geological as well as faunal evidences.

Many deposits in the valleys of streams that formed drainage channels from the Wisconsin ice sheets probably contain the remains

of faunas belonging to the Sangamon or Peorian intervals, and the study of this material from a wide area would aid very largely in understanding the interglacial and postglacial migrations of many

TABLE III

LAND SHELLS OF TWO INDIANA DEPOSITS

Lawrenceburg	Flat Rock River
Vallonia pulchella	.....
Cochlicopa lubrica	.....
Gastrocopta contracta	*Gastrocopta contracta*
Gastrocopta armifera	.....
Pupoides marginatus	.....
Succinea species	.....
.....	*Succinea avara vermeta*
Helicodiscus parallelus	*Helicodiscus parallelus*
Pyramidula perspectiva	.....
Pyramidula cronkhitei anthonyi	.....
Pyramidula solitaria	*Pyramidula solitaria*
Pyramidula alternata	*Pyramidula alternata*
Gastrodonta ligera	*Gastrodonta ligera*
Vitrea hammonis	*Vitrea hammonis*
Vitrea indentata	*Vitrea indentata*
Circinaria concava	*Circinaria concava*
Polygyra monodon	*Polygyra monodon*
Polygyra stenotrema	*Polygyra stenotrema*
Polygyra mitchelliana	.....
.....	*Polygyra clausa*
Polygyra thyroides	*Polygyra thyroides*
Polygyra pennsylvanica	.....
Polygyra elevata	*Polygyra elevata*
Polygyra appressa	.....
Polygyra palliata	*Polygyra palliata*
Polygyra multilineata	.....
Polygyra zaleta	*Polygyra zaleta*
Polygyra albolabris	.....
Polygyra profunda	*Polygyra profunda*
Polygyra inflecta	*Polygyra inflecta*
Polygyra tridentata	*Polygyra tridentata*
.....	*Polygyra fraudulenta*

species of mollusks. A case in point is the presence of the minute fresh-water snail known as *Pyrgulopsis sheldoni* in this old interglacial deposit. This species was described from material dredged

in Lake Michigan, off Racine, Wisconsin, at a depth of thirty fathoms. Additional records from both recent and fossil faunal areas are needed to understand the distribution of this tiny species. Geologists or others who discover such deposits should carefully collect the material, noting rather minutely the stratigraphy, and send the material, unsorted, to some competent malacologist for study. Such deposits occur plentifully in Iowa, Wisconsin, Illinois, Michigan, Indiana, Ohio, and Maine, and also in parts of other states which were overridden by the great ice sheets.

The material described in this paper forms a part of the Pleistocene collection of the Museum of Natural History of the University of Illinois.

ANNOTATED LIST OF MOLLUSCA FROM THE POSTGLACIAL DEPOSITS NEAR RUSH LAKE, LOGAN COUNTY, OHIO

Unionidae

Anodonta species. Fragments of a naiad, apparently a thin-shelled *Anodonta*, occur with the material. Evidently rare, as but few fragments were found.

Sphaeriidae

Sphaerium sulcatum (Lamarck). This large *Sphaerium* is abundant in the material from the Ohio deposit and is the only member of the genus found. These shells vary in form more than do most individuals of the recent fauna.

Musculium rosaceum (Prime). A dozen odd valves of a *Musculium* are referred to this species by Dr. Sterki, who says: "*Musculium*, different forms, but apparently of *rosaceum*, deformed."

Pisidium compressum Prime. A common, almost abundant species in this marl bed, but none typical. Sterki says: "near variety *laevigatum*."

Pisidium variabile Prime. About as common as *P. compressum*. Sterki states that this species is difficult to separate from *compressum*, especially among fossil individuals. This fact would indicate a common origin for both species, and the study of the Pleistocene material is, therefore, very important from the standpoint of geological evolution.

Pisidium tenuissimum Sterki. The most abundant species of Sphaeriidae in the deposit and quite typical of the species. This *Pisidium* seems to be a common Pleistocene fossil, occurring in widely separated deposits in Maine, Michigan, Ohio, and Illinois. In the deposits at Urbana, Illinois, believed to be pre-Wisconsin, a variety of this species—*calcareum* Sterki—is the most abundant mollusk in the material examined (see Baker, 1918, p. 663). It is quite significant that *tenuissimum* has not yet been found in deposits older than post-early Wisconsin; none are recorded from Sangamon or Peorian deposits. It is absent from the Indiana deposits discussed in this paper and believed to be of Sangamon age.

Pisidium medianum Sterki. A score of Pisidia, with small, thin shells and very prominent beaks, are referred to this species by Dr. Sterki.

Pisidium noveboracense Prime. *Pisidium pauperculum* Sterki. Two valves each of the foregoing species were identified from the material by Dr. Sterki. They are both typical of the species.

Valvatidae

Valvata tricarinata (Say). This is one of the most abundant species in this marl deposit. The majority of the specimens have three strong raised keels and are in every way typical of the species. In a few forms, however, the central carina is faintly developed, showing a variation toward the next variety.

Valvata tricarinata perconfusa Walker. About 10 per cent of the carinate Valvatas belong to this variety. There is some variation in the smooth space between the carinae on the shoulder of the whorl and on the base of the shell, there being in some specimens a faint ridge indicating the position of the central carina in typical *tricarinata*.

Valvata tricarinata unicarinata DeKay. A single specimen of DeKay's variety was found among several hundred *tricarinata*. This variety appears to be rare among both fossil and recent members of the species.

Valvata sincera Say. Three specimens of this characteristic species were picked out of a quart or more of marl specimens

(about 20,000 specimens), indicating that this species is very rare in this marl deposit. Compared with the same species from the marl deposit in Urbana, Illinois, the Ohio shells are a trifle more depressed.

Amnicolidae

Amnicola walkeri Pilsbry. Most of the Amnicolas referred to this species are quite typical, agreeing with Walker's figure in the *Nautilus* (Vol. XIX, Pl. V, Fig. 12). A few individuals have a higher spire with strongly rounded whorls and a very deep suture, i.e., scalariform. The largest specimen measures about 2.5 mm. in length. This characteristic species is not common in this deposit, only about fifty specimens being found in picking over a quart of material.

Amnicola lustrica Pilsbry. Variety. "Larger, more solid, with the lip much thickened within" (Pilsbry). This *Amnicola* is, equally with the following species, the most abundant species in the deposit, nearly 40 per cent of the bulk of a quart being composed of these two species of *Amnicola*. There is some variation in the width of the shell and in the height of the spire, the whorls of which, in some individuals, are quite round, with very deep sutures. A single specimen is so decidedly scalariform as to render it quite unrecognizable without its presence in the other material. Several specimens of this variety measure 4.5 mm. in length. In most individuals the inner lip (peristome) touches the parietal wall, but in others it is separated by a deep suture and the edge of the aperture is entirely separated from the body whorl. The same form of *lustrica* occurs in post-Wisconsin deposits of the Chicago region.

Amnicola winkleyi leightoni Baker. This *Amnicola* (described in the *Nautilus*, Vol. XXXIII) is related to *winkleyi* Pilsbry, described from Saco, Maine. It is uniformly wider, with somewhat shouldered whorls. Together with *Amnicola lustrica* variety, it is the most abundant species in this deposit. That a form related to the Maine shell should be found so far removed from the original locality is surprising, particularly as it occurs in a deposit of late Pleistocene age. The specimens have been examined by Dr. Pilsbry, who indicated their relationship to his Maine species and who agreed with the author as to their distinctness as a race believed to be extinct.

Planorbidae

Planorbis campanulatus Say. A dozen specimens of this species, mostly mature, occurred in the material examined. The adults are of normal size and typical form.

Planorbis antrosus Conrad. A fairly abundant species of large-sized individuals, mostly mature. There is considerable variation among the specimens, especially in the shape of the aperture, which has a tendency to become bell-shaped. A number of individuals approach variety *aroostookensis* Pilsbry, and one specimen would certainly be called variety *portagensis* Baker, if found in Maine. Several specimens have a number of rounded ridges on the body whorl near the aperture; these indicate the location of former apertures.

Planorbis antrosus striatus Baker. About 10 per cent of the *antrosus* may be referred to this variety with strong spiral striation. This is very strongly marked in the majority of the fossils of this deposit.

Planorbis altissimus Baker. This small *Planorbis*, first described from marl deposits at Urbana, Illinois, proves to be widely distributed and to be the common *Planorbis* of the *parvus* group in the marl deposits. It is very variable, only a small percentage being typical as figured in the original description (Baker, 1918, p. 94). The aperture varies from rounded to elliptical and may be deflected to a marked degree or placed in an almost continuous line with the body whorl. In all specimens examined, however, the upper part of the aperture forms a distinct shoulder and the whorls are more or less flat-sided, features not found in true *parvus*, which is normally a smaller shell. *Altissimusis*, after *Amnicola lustrica* and *A. winkleyi leightoni*, is the most abundant shell in this deposit.

Planorbis deflectus Say. Three adult individuals of this small *Planorbis* were found in the material examined. The peripheral keel is very marked in these specimens, and the aperture varies in the degree of deflection, in one specimen being almost basal. The largest individual measures 6.5 mm. in greatest diameter.

Planorbis hirsutus Gould. A single specimen seems referable to this species, having the less conspicuous keeled periphery and rounded whorls of *hirsutus* from Massachusetts. This species seems quite separable from *deflectus*.

Planorbis exacuous Say. This flat, lens-shaped *Planorbis* is fairly common in this deposit. The specimens are of large size, several individuals measuring 6 mm. in greatest diameter.

Lymnaeidae

Galba palustris (Müller). A single broken specimen of a lymnaeid is referable to this protean species. When perfect it must have measured nearly 40 mm. in length.

Galba obrussa decampi (Streng). This small lymnaeid is quite common in the deposit. It exhibits more or less variation, principally in the degree of elevation of the spire, in the convexity of the whorls, and in the shoulder of the whorls. This species is characteristic of the cold waters of the early Wisconsin ice recession, in which it lived in considerable abundance. It is apparently much less common living in the recent fauna than it was in postglacial or interglacial times.

Physidae

Physa anatina Lea. This large *Physa* is apparently a form of Lea's species, which occurs abundantly in the states west of the Mississippi River. It is recorded from Michigan and is said to range clear across the southern part of this state (see Walker). It is also recorded from Hardin, McHenry, and Adams counties, Illinois (see Baker, *Ill. Cat.*). There seems to be no reason why it should not be found as far east as Ohio.

The Ohio shells differ from typical *anatina* in being larger, with a wider body whorl and aperture and more flat-sided spire whorls. Adult individuals are not common in the deposit, but immature shells of four whorls are almost abundant. Variation is so great in this genus that it has not been thought best to bestow a name on this form, although it differs more or less widely from the average recent shells of *anatina*.

Ancylidae

Ferrissia parallela (Haldeman). A single specimen of this fresh-water limpet was found in the material examined. As about 20,000 shells were picked over it must be considered very rare. The specimen is typical.

ANNOTATED LIST OF MOLLUSCA FROM SANDY LOAM DEPOSITS AT FLAT ROCK RIVER, BARTHOLOMEW COUNTY, INDIANA. BELIEVED TO BE REFERABLE TO THE SANGAMON INTERGLACIAL INTERVAL

Unionidae

Amblema undulata (Barnes). Mr. Fluck reports this large naiad as occurring in the deposit.

Elliptio crassidens (Lamarck). A right valve 47 mm. in length is quite characteristic of this heavy-shelled naiad, which is common in the Ohio and Wabash rivers.

Elliptio gibbosus (Barnes). Reported in the deposit by Mr. Fluck.

Actinonaias ellipsiformis (Conrad). A broken right valve and two immature shells (right and left valves) somewhat broken are referred to this common Indiana species. They are thinner, on the average, than recent shells of this species.

Carunculina glans (Lea). A left valve of a female shell 31 mm. in length appears not to differ from recent shells in any important degree.

Lampsilis ventricosa (Barnes). This species is reported from the deposit by Mr. Fluck.

Species incerta cedis.

A portion of the umbonal and lateral tooth region of an unknown naiad also occurs in the material examined. It belongs to the heavy-shelled species, like *rubiginosus* and *undatus*, but is quite unidentifiable.

Sphaeriidae

Sphaerium solidulum (Prime). A number of valves of this common species occur in the material examined, but they are not very characteristic, many individuals varying considerably from the typical form. The young and immature shells are much more typical.

Sphaerium stamineum (Conrad). Three valves of a *Sphaerium* are referred to this species by Dr. Sterki, with doubt.

Sphaerium striatinum (Lamarck). This species is about as abundant in this deposit as *solidulum*. There are many different forms, and the majority of the specimens are young or immature.

Sphaerium fabale Prime. One valve of this characteristic species occurred with the other *Sphaeria*. It is evidently very rare.

Pisidium virginicum (Gmelin). This large *Pisidium* is quite common in this deposit and also quite typical.

Pisidium compressum Prime. This is the most abundant *Pisidium* in the Indiana deposit, as it often is in most recent and fossil collections. The Indiana specimens are more typical than those from the Ohio deposit.

Pisidium cruciatum Sterki. A half-dozen valves, mostly immature, occur in the material.

Pisidium kirklandi Sterki. Fairly common but very characteristic of the species as found living.

Pisidium fallax Sterki. A half-dozen valves, small and slight, are referred to this species by Dr. Sterki.

Pisidium pauperculum Sterki. Two valves of a *Pisidium* are identified with this species by Dr. Sterki.

Pisidium noveboracense Prime. A score of odd valves, small and largely immature, are referred to Prime's species by Dr. Sterki. They are not typical of the species as found living today.

Pisidium abditum Haldeman. Two valves are doubtfully referred to *abditum* by Dr. Sterki.

Valvatidae

Valvata tricarinata (Say). Six young and immature specimens of this carinate *Valvata* were found in the material. The spire is rather depressed and the specimens somewhat resemble *Valvata bicarinata normalis* Walker.

Amnicolidae

Amnicola limosa parva (Lea). A score or more specimens of this variety of *limosa* occurred in the collection. The shells vary from depressed to somewhat elongated. The whorls are all tumid and strongly shouldered at the suture. The spire varies in height and the aperture in rotundity. More than half of the shells are immature.

Amnicola walkeri Pilsbry. A single, large, typical specimen of this *Amnicola* was found in the collection. It is larger than the individuals of the same species from the Ohio deposit.

Amnicola lustrica (Pilsbry). Apparently typical examples of this common *Amnicola* occur more or less abundantly in the Indiana deposit. These are different from the *Amnicola* which occurs so abundantly in the Ohio deposit, and also commonly in the deposits in and about the Chicago region, which has a larger shell with more elongated spire and thickened lip margin. Many of the Indiana shells are immature.

Pyrgulopsis sheldoni (Pilsbry). The presence of this tiny species in these deposits is surprising, the species having been originally described from material collected in Lake Michigan, off Racine, Wisconsin, and dredged from a depth of thirty fathoms (Pilsbry, 1890, Vol. IV, p. 53). Its occurrence in an interglacial deposit far removed from the original locality and in an entirely different ecological environment, a river, is very interesting. These fossils are possibly the ancestors of the species that later restocked the waters of Lake Michigan after the recession of the Wisconsin ice. It should be looked for in other Pleistocene deposits. *Sheldoni* is not uncommon in the Indiana deposit, but the shell is smaller on the average than that of recent specimens. The identification of this tiny species has been confirmed by Dr. Bryant Walker.

Somatogyrus depressus Tryon. The half-dozen specimens of this species are typical.

Pomatiopsis lapidaria (Say). The single specimen occurring in the material is normal in size and general shape, but the whorls are rounder and the sutures more deeply impressed than is usually the case among recent shells of this species.

Pomatiopsis cincinnatiensis (Lea). Four specimens of this smaller species of the genus occurred. They do not differ from recent shells.

Pleuroceridae

Goniobasis semicarinata (Say). A *Goniobasis* abundant in the deposit is referred to Say's *semicarinata* by Mr. Calvin Goodrich, to whom specimens were sent for examination. It is a long-spired, graceful shell which seems very characteristic. In the lot from Bartholomew County there is little variation except in the comparative width of the last whorl.

Viviparidae

Campeloma integrum obesum (Lewis) Tryon. All of the Campelomae in the collection (and these shells are quite abundant) appear referable to this race of *integrum*. A few individuals have a more elongated spire and more ovate shell and might be referred to *integrum*. The variation, however, is all toward the obese type of shell and it seems best to refer all to the race. The majority of the individuals are adult. The shells are quite solid and heavy.

Ancylidae

Ferrissia rivularis (Say). That such fragile shells as the Ancylidae should be preserved in a flood-plain river deposit is surprising. Five specimens of this river limpet occurred in about two quarts of material examined. The specimens are fairly well preserved.

Physidae

Physa crandalli Baker. A heavy-shelled *Physa* with thick, reflexed inner lip and deep-sutured whorls is referred to this species. Only one specimen out of a score or more is adult. The same species has been reported by Daniels from Indiana in the recent fauna of Knox County (Daniels, 1903, p. 603).

Planorbidae

Planorbis antrosus Conrad. The *antrosus* from the Indiana deposit are smaller than those from the Ohio deposit. The aperture does not show a tendency to become bell-shaped as in so many of the Ohio specimens. Only seven individuals, mostly immature, were found in the material from the Indiana deposit.

Planorbis parvus Say. This small *Planorbis* seems to be typical *parvus* and not *altissimus* which is so abundant in the Ohio deposit. It is the same size as specimens of *parvus* from Philadelphia and about half the size of *altissimus*.

Lymnaeidae

Galba humilis modicella (Say). The only lymnaeid in the Indiana deposit is referable to *modicella*, the individuals of which, mostly immature, are similar to the recent shells of this species from the state. *Obrussa decampi*, so common in the Ohio deposit, is apparently not found in these Indiana beds.

Pupillidae

Gastrocopta contracta (Say) = *Bifidaria contracta*. Apparently rare in the deposit as but two specimens were found. These shells are typical but smaller than the average of living *contracta*.

Succineidae

Succinea avara vermeta Say. A single specimen of this race of *avara*, about 5 mm. long, was found in the material. It is, therefore, to be considered as rare.

Endontidae

Helicodiscus parallelus (Say). This common and widely distributed land shell occurred infrequently. The shells are smaller than those of the recent fauna and the spiral striation is but faintly developed.

Pyramidula solitaria (Say). The most abundant mollusk in the deposit. There is considerable variation among the individuals in the height of the spire. The largest specimen measures 30 mm. in greatest diameter. The majority of shells are typically banded. In a few individuals the reddish bands are very wide, leaving a broad peripheral band of white.

Pyramidula solitaria albina (W. G. Binney). A few individuals of *solitaria* without bands occur with the typically banded specimens.

Pyramidula alternata (Say). Found infrequently as compared with *solitaria*. As in the recent shells of this species the fossil examples vary in the height of the spire and in the degree of carination of the periphery of the last whorl. The color varies from albino to the most marked flames of red.

Pyramidula alternata alba (Tryon). Three examples of the albino variety were found associated with the more typical forms. The variety is apparently rare.

Zonitidae

Gastrodonta ligera (Say). This zonitoid land shell occurs rarely in this deposit. The few specimens found are smaller than shells from the recent fauna.

Vitrea indentata (Say). Two immature but characteristic examples of this imperforate *Vitrea* were found in the sand taken from the larger shells.

Vitrea hammonis (Ström.). Two typical specimens of this species were found in the sand from the interior whorls of a specimen of *Pyramidula solitaria*. This small land mollusk, as well as the other species of this family, appears to be very rare.

Circinariidae

Circinaria concava (Say). Not uncommon and as large as the recent shells from Indiana. The aperture is rounder in the fossil shells than in the recent individuals, and the peculiar flattening of the upper part of the outer lip is rarer in the fossil specimens.

Helicidae

Polygyra tridentata (Say). *Polygyra fraudulenta* Pilsbry. These two common species are apparently not abundant in the deposit in question.

Polygyra inflecta (Say). As but two individuals of this species were found in the large quantity of material examined it must be rare among the fossil land shells of this part of Indiana. The shells are apparently normal in both size (12 mm.) and form.

Polygyra profunda alba Walker. Nearly all of the specimens referred to *profunda* belong to the variety *alba*. One individual occurred which has the usual narrow bands on the last whorl and in addition has several large rosy blotches of color on the last half of the body whorl.

Polygyra zaleta (Binney) = *exoleta* (Binney). *Zaleta* is apparently rather rare, only seven specimens being found among several hundred land shells in the material. One specimen has a well-marked parietal tooth; the others are toothless.

Polygyra elevata (Say). Next to *Pyramidula solitaria*, *elevata* is the most abundant land mollusk in the deposit. In size and form they do not differ from the recent individuals. The same variation in height of spire noted among recent shells is also present in the fossil form.

Polygyra thyroides (Say). Of the twelve specimens of this species examined, three have a well-marked tooth on the parietal wall; the others are toothless. There is some variation in size, the extremes being 22 and 28 mm. in greatest diameter.

Polygyra clausa (Say). Characteristic shells of this small *Polygyra* are common in the deposit. These do not differ materially from the recent forms of this species.

Polygyra fraterna (Say). This small *Polygyra* is reported by Mr. Fluck, who has found it more or less common at times.

Polygyra stenotrema (Fer.). Typical forms of this species are not uncommon in the deposit.

LIST OF WORKS CONSULTED

BAKER, FRANK COLLINS

1906. "A Catalogue of the Mollusca of Illinois," *Bull. Ill. State Lab. Nat. Hist.*, Vol. VII, pp. 53–136.

1918. "Post-glacial Mollusca from the Marls of Central Illinois," *Jour. Geol.*, Vol. XXVI, pp. 659–71.

1919. "Description of a New Species and Variety of Planorbis from Post-glacial Deposits," *Nautilus*, Vol. XXXII, pp. 94–97.

BILLUPS, A. C.

1902. "Fossil Land Shells of the Old Forest Bed of the Ohio River," *Nautilus*, Vol. XVI, pp. 50–51.

DANIELS, L. E., and BLATCHLEY, W. S.

1903. "On some Mollusca Known to Occur in Indiana," *27th Annual Report, Dept. of Geol. and Nat. Res. Indiana*, pp. 579–680.

LEVERETT, FRANK

1902. "Glacial Formations and Drainage Features of the Erie and Ohio Basins," *Mon. U.S. Geol. Surv.*, No. XLI.

PILSBRY, HENRY A.

1890. "Preliminary Notices of New Amnicolidae," *Nautilus*, Vol. IV, pp. 52–53.

QUINN, E. J.

1912. "Soil Survey of Bartholomew County," *36th Annual Report, Dept. of Geol. and Natural Res. Indiana*, pp. 320–34.

FACTORS PRODUCING COLUMNAR STRUCTURE IN LAVAS AND ITS OCCURRENCE NEAR MELBOURNE, AUSTRALIA

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The following notes on columnar structure owe their origin to a study of the basalt in the Sydenham area, 15 miles northeast of Melbourne, Australia. There, a young stream, Jackson's Creek, has sunk its bed in the Upper Kainozoic lava flows to a depth of 250′. At some points the Silurian and Upper Ordovician sediments are exposed in its bed but at many other places the stream has not yet reached the level of the old valleys and a great thickness of basalt is exposed to view.

The best columns are found along Jackson's Creek in an area 1¼ miles in length. In it is a low scoria cone of the same age as the lava. Three miles to the north is a line of volcanoes from which the later lava floods came. Of the columns the best perhaps are those known as the Sydenham Organ Pipes. These are 102′ high, are perfectly developed, and give examples of the various structures discussed in this short paper.

1. *Cause of columnar structure.*—The attitude, size, shape, and regularity of the columns depend upon (*a*) the viscosity of the lava; (*b*) the temperature of the lava; (*c*) the rate of cooling; (*d*) the regularity of cooling; (*e*) the homogeneity of the lava. Shallow surface flows are much disturbed by movement and are usually distorted by folded-in masses of scoriaceous material, so that homogeneity is lost. Cooling is irregular and columns do not form. The importance of homogeneity as a factor in columnar formation cannot be emphasized too much. The great controlling factor in the formation of columns is contraction due to cooling. The rock, on cooling, tends to contract but all solids have the power to extend somewhat under tension. When the tension due

to contraction on cooling is able to overcome this power of extension, the rock cracks.

Let us consider in the first place a lava mass cooling from one surface only, the top of the flow (Fig. 1). It is evident that the surface will cool very rapidly owing to the scoriaceous nature of the surface, the convection currents in the air above the heated rock, the volcanic rain (if near a vent), and the collection of water on the warped surface. Thus a solid crust will form over the molten lava and this liquid will cool very slowly because rock is a very poor conductor of heat. While cooling and shrinking in the liquid state, it will adjust itself to the tension by a movement of the liquid, but when the lava solidifies from *b* to *c* (Fig. 1) the rock is subjected to tension in horizontal and vertical directions. The vertical tension is relieved by movement of the liquid beneath *c* and by the shortening of the column *bc*. Vertical tension at this stage does not cause joints in the rock but the horizontal tension can only be relieved by cracking. Mallet[1] puts the temperature of cracking between 315° C. and 500° C., and points out that the temperature is lower when the rate of cooling is very slow. He also shows that if the rock were perfectly homogeneous the surface would be covered with cracks separating the surface into equal areas, i.e., triangles, squares, or hexagons.[2] The smallest amount of work is done by separating the surface into hexagons rather than into squares or triangles. These cracks would extend down into the hot solid rock only a short distance, i.e., to that point where the tension was equal to the extensibility. As the rock cooled, the cracks would extend downward and at the same time the deeper liquid lava would be solidifying and shrinking from two causes: cooling and crystallization. The slower the cooling the more complete the crystallization and therefore the greater the contraction. We

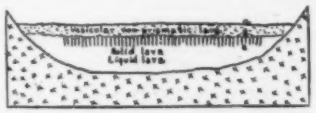

FIG. 1.—Section showing how columns are formed in the brittle solid lava, when tension due to contraction overcomes the expansive power of the lava. Columns are not formed near the surface.

[1] R. Mallet, *Phil. Mag.*, L (1875), p. 130.

[2] *Op. cit.*, pp. 125–30.

thus see that in a homogeneous lava, vertical cracks arranged in hexagons, slowly penetrate the solid lava from above, downward. Solidification of the lava precedes the cracking.

The size of the columns depends chiefly on the temperature and rate of cooling. The more rapidly cooled a flow is the thinner will be the columns.

Owing to the fact that lava masses are seldom homogeneous (on account of included gases, convection currents within, variation in chemical composition, included fragments, etc.) it seldom, if ever, occurs, that only hexagonal prisms are formed. It does not need the fact that olivine crystals have been found divided by vertical joints, nor the preservation of flow structure in glass to show us that the splitting took place in solid lava.[1] It is difficult to imagine liquid or even plastic lava cracking. Tension in that case is relieved by flowage, not by cracking.

For the following reasons the writer believes that columnar structure in basalt is due to slow rather than rapid cooling:

1. Basalt has a very low thermal conductivity and therefore great thicknesses of molten basalt must necessarily cool slowly. The fact that columnar basalt is not well developed where flows are thin appears to be due to two factors: (*a*) heterogeneity of the lava, (*b*) rapid cooling of the thin flow.

2. Cracking takes place in the hot solid rock when the contraction becomes greater than the expansion under tension. The rock is able to resist parting for a longer period when the tension is very slowly increased by slow cooling. If tension is more rapidly increased the flow will break into thin columns or fragments. These statements are based on physical laws. The rate of cooling at the upper surface is much more rapid than at the lower because convection currents in the air above rapidly convey away the heat but the valley floor being a poor heat conductor offers much resistance to the transference of heat. In a thick flow, columns grow from all cooling planes. The upper columns are found to rest on thick basal columns and this fact upholds the statement that the size of columns is determined by rate of cooling.

[1] J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886), p. 324; R. B. Sosman, *Jour. Geol.*, XXIV (1916), p. 218.

3. The fact has frequently been recorded[1] that the upper layer of rock is not columnar but fragmental, platy, ropy, or scoriaceo This fact shows that if cooling is rapid, columns are not formed, for the surface layer is cooled with very great rapidity. If cooling is very rapid contraction is likely to cause fragmental partings since the isothermal planes would probably be irregularly spaced through the flow.

4. In the rock sections of columnar basalt examined very little glass was noted, whereas the surface rock contained a considerable amount of glass. The holocrystalline nature of the columnar basalt strongly suggests slow rather than rapid cooling.[2]

2. *Ball-and-socket structure.*—The cross joints are secondary, i.e., they are formed after the columns. This is shown by the fact that they never continue across from one column to another. The vertical columns continue to shrink as they cool. Horizontal contraction simply causes a widening of the vertical joints, but tension in other directions can only be relieved by cracking.

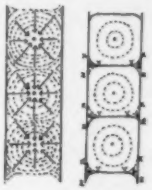

FIG. 2 FIG. 3

FIGS. 2 and 3.—Onion structure and spheroidal weathering. Centers of contraction along the columns cause concentric planes of weakness which, on weathering, develop into the well-known "onion structure." The solid angles *a* and *b*, which tend to break off, are due to these concentric planes of contraction. Ball-and-socket joints are formed between the adjacent spheroids.

There are necessarily centers of contraction distributed equally along each column (if lava is homogeneous) and the particles will concentrically be drawn toward these points. This causes not only concentric weakenings and cracking but also a well-defined horizontal joint midway between any two centers of contraction (Fig. 2). Mallet[3] says that the concave surfaces face the direction of cooling. This is not true in the areas I have studied, for adjacent columns have the cups facing directions regardless of the cooling surface.

[1] J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886), p. 325. [2] *Op. cit.*, p. 331.

[3] R. Mallet, *Phil. Mag.*, L (1875), p. 204; J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886), p. 329; R. B. Sosman, *Jour. Geol.*, XXIV (1916), p. 229.

We can say that either the convex or the concave surface faces the direction of cooling. It is also evident that the solid angles, *a* and *b*, are likely to be broken off along *YZ* and *YX* (Fig. 3), since these are planes of contraction and weakness. This seems to explain very simply a well-recognized structure that has given rise to much debate[1] (Fig. 3).

FIG. 4.—"Dutch-cheese" structure. Each spheroid is about eight inches thick. ("Organ Pipes," Sydenham, Australia.)

The above explanation for the ball-and-socket structure also explains the prevalence of spheroids in the columns. I cannot believe that they are due to weathering[2] or segregation, but rather to the concentric spheres of contraction. The spheroids are not found passing from one column to another. In the diagram (Fig. 3) each column is seen to be divided actually or potentially into blocks, each composed of concentric spheres separated by a contraction crack or line of weakness along which weathering will later take place and finally give rise to "onion structure."

3. "*Dutch cheeses.*"—This structure is very common on slightly weathered basalt columns (Fig. 4). The oblate spheroids are seen piled one above the other. They appear to be oblate for this reason: Contraction along *ax* (Fig. 5) is easier than along *ab*,

[1] T. G. Bonney, *Quart. Jour. Geol. Soc.* (1876), p. 153; R. Mallet, *Phil. Mag.*, L (1875), p. 205; J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886); R. B. Sosman, *Jour. Geol.*, XXIV (1916).

[2] J. Thomson, *British Association Reports* (1863), p. 89; R. Mallet, *Phil. Mag.*, L (1875), p. 220.

because no tearing apart of the crystals is necessary along *ax*. In order that tension in all directions may be approximately equal, *am* must be shorter than *ax*. Therefore, the shape of the spheroids is dependent on the ratio of the tension between *ax* and *am*. The shape of the spheroids is also dependent on the downward pressure of the columns. This pressure tends to resist horizontal cracking and therefore the greater the downward pressure the more prolate the spheroid will be. The actual shape of the spheroid is determined by the downward pressure of the column tending to make it prolate, and the difference in tensions along *am* and *ax* which tends to make the spheroid oblate.

FIG. 5.—Dutch-cheese structure. The shape of the spheroids depends on the balance between the difference in tension between *ak* and *am*, which tends to make the spheroid oblate and the downward pressure of the column tending to make the spheroid prolate.

4. *Chisel structure.*—At the "Sydenham Organ Pipes" horizontal markings $\frac{3}{4}''$ to $2''$ apart, are seen

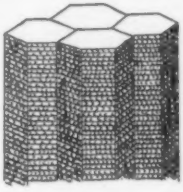

FIG. 6

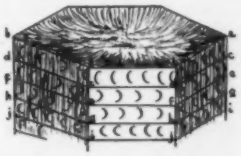

FIG. 7

FIGS. 6 and 7.—Diagrammatic section showing horizontal bandings *abab*, *cdcd* round the columns. Rough chiselings are shown on each band.

circumscribing most of the columns (Figs. 6, 7, and 9). The horizontal lines are found along the whole length of the columns and between them there are peculiar irregularly curved lines similar to those made by roughly chiseling wood (Figs. 7 and 9). The horizontal lines appear to represent successive stages in which the columns were formed, i.e., as cooling proceeded, the vertical plane *abcd* extended to *ef*, then to *gh*, and so on. The "chiselings" curve sometimes to the left, sometimes to the right, and are probably due to the heterogeneity of the rock as it parted.

5. *Columns formed by cooling from two opposing surfaces.*—Cooling takes place not only from the upper surface but also from

the floor. The upper surface rapidly parts with its heat by air convection currents and convection along the vertical joints. Heat is only slowly lost from the bottom surface because convection in

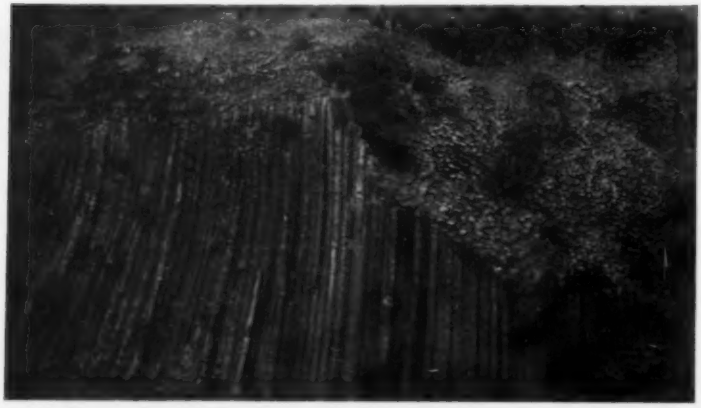

FIG. 8.—"The Organ Pipes." These basaltic columns are 102′ high and are found on Jackson's Creek, Sydenham, Australia.

FIG. 9.—Chisel structure. Several basaltic columns are shown with characteristic horizontal banding. In each band the chisel structure can be seen. ("Organ Pipes," Sydenham, Australia.)

the liquid rock seems to be comparatively unimportant, the conductivity of the rock beneath is very low, and the loss of heat by rising gases is unimportant in lowering the temperature of the bottom layers. The isothermal planes will therefore be widely separated in the upper layers and closely packed together in the lower. Two sets of columns will be formed. The upper are long, thin, and often irregular, while the lower set are short, thick,

FIG. 16.—Weathered chisel structure. The chisel markings have been weathered off but the horizontal bandings have developed into platy structure. (Jackson's Creek, Digger's Rest, Australia.)

and much more perfect, owing to the homogeneity of the lower lava (Figs. 11 and 12).

It must be remembered that straight hexagonal columns are produced only in regularly cooling, quiet, homogeneous lavas. The upper part of the flow is more heterogeneous than the lower because (*a*) gases from the lower layers are irregularly distributed near the top; (*b*) the upper surface is churned to some extent by the movement; (*c*) volcanic rain percolates the vesicular lava; (*d*) water may collect on the partially cooled lava. These four factors tend to produce a heterogeneity in the upper part of the flow and therefore only very imperfect columns, if any, are formed.

As the thin upper and the massive lower series of columns approach one another their direction will be influenced by the plane of the isotherms of each series. Both sets are perpendicular to the planes of the isotherms (Fig. 13). Finally the two planes merge into one another and if both sets of columns are vertical, there will be a straight horizontal plane junction which simulates the junction between two lava flow (Figs. 11 and 13), but the absence

FIG. 11.—Junction of the upper and lower columns of a lava flow. The sharp division suggests the junction of two flows, but only one flow is represented. The lower columns are much more massive than the upper. (Jackson's Creek, Sydenham, Australia.)

of vesicles and scoriaceous material, the exact similarity in density and texture of the two series at their junction, and the actual blending of the columns at times show that they belong to the same flow.

The resting of thinner columns on more massive basal ones is very common. They are described by Scrope[1] and Iddings[2] and are well shown at Sydenham. Dykes commonly show the edge of the division plane between two sets of columns.

[1] G. P. Scrope, *Volcanoes* (1862), p. 94.

[2] J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886), p. 322.

6. *Columns formed from inclined cooling surfaces.*—The dotted lines on Figure 13 represent the edges of the isothermal surfaces. Columns form at right angles to these surfaces. The isotherms shown in Figures 12 and 13 give data for the rate of formation of the columns, their size, and their direction. The closer the isotherms the larger are the columns because the lava is able to resist a greater tension without cracking when that force is gradually applied. Columns from the two inclined surfaces approach one another and meet along a major joint plane which would be enlarged by drainage. Note that along this major joint the columns curve toward the higher temperatures.

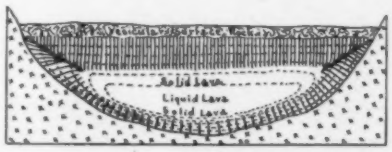

FIG. 12.—Section showing lava cooling from two surfaces, and columns penetrating the solid lava as cooling proceeds. Columns are perpendicular to the isothermal planes and where two cooling surfaces are inclined to one another a major joint plane separates the two sets of columns.

7. *Bent columns.*—These (Fig. 14) are formed in cases where the isotherms are not parallel to one another. For reasons such as those enumerated below, the cooling in one direction is more rapid than in another. The columns bend in the direction of greatest cooling (Fig. 15). Dotted lines represent edges of isothermal surfaces. The following are suggested causes for change in direction of cooling: (1) presence of scoria, etc., in close proximity to the lava; (2) irregularities in the valley floor; (3) the warping of the lava's upper surface; (4) a scoriaceous and vesicular surface; (5) included gas, water, etc., in the lava; (6) convection currents in the air above the lava; (7) convection currents in the lava; (8) penetration of water into the lava and scoria; (9) rain from the volcano; (10) movement

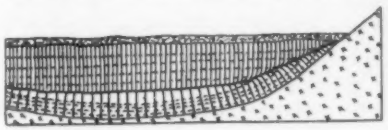

FIG. 13.—Junction of the slender upper columns and the massive basal columns of a lava flow. The junction somewhat resembles the junction between two lava flows.

of the liquid or plastic lava and thereby of the isotherms; (11) rise of steam from an overwhelmed stream; (12) chemical variation in the lava with corresponding change in thermal conductivity.

FIG. 14.—Bent columns. (Jackson's Creek, Sydenham, Australia.)

It is not likely that lava columns bend after they are formed, for if lateral pressure were sufficiently strong, it would fracture the brittle columns but not bend them. The plastic state, when the lava would yield to lateral pressure, was lost when the molten mass crystallized.

8. *Convection as a factor on column production.*—R. B. Sosman[1] in 1916, stated that many, if not most, lava columns were due to convection currents in the molten flow. He said convection columns are characterized by the fact that hexagonal columns and angles of 120° predominate, while the majority of contraction columns are pentagonal.[2] After testing some hundreds of columns in the Sydenham area I am unable to agree with him in several respects. The attitude of the columns there stamps them as being definitely due to contraction, not convection, and yet 40 per cent are hexagonal, 22 per cent heptagonal, 22 per cent pentagonal, 13 per cent octagonal and 3 per cent quadrilateral, and the great majority of the angles are

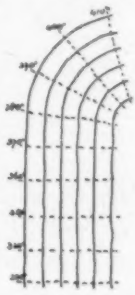

FIG. 15.—Bent columns. Diagram showing the relation of the attitude of the columns to the isothermal planes.

[1] R. B. Sosman, *Jour. Geol.*, XXIV (1916), pp. 224, 228, 233.

[2] *Ibid.*, pp. 225–26.

between 120° and 130°. From these observations it is clear that it is not safe to classify columns as due to contraction or convection by their shape and angles.

Close to the "Sydenham Organ Pipes" there are a number of huge squat irregular basaltic columns about 10′ in diameter. The flow is thin and the shape of the great blocks seems to be determined by convection which left its record in them by vesicles and when the rock contracted through loss of heat the cracks formed along the lines of vesicles (Fig. 16). The vesicles are pulled round in just the way one would expect if convection currents were the cause. There are centers round which the currents traveled and these tend to be hollowed out leaving holes 3′ to 4′ across. It is possible that the drawn-out vesicles are due to the movement of the lava before it came to rest, but the fact that most of these squat columns seem to have the hollow or nucleus suggests convection. Contraction due to shrinkage subsequently tends to crack the rock along the lines where the currents rose or sank.

FIG. 16.—Convection currents in basalt. The direction of the vesicles and the occurrence of the nuclei suggest that the molten lava was disturbed by convection currents. The vertical joints occur where the long axes of the vesicles are vertical.

Convection columns in this area are either very unimportant or absent so that the conclusions drawn in R. B. Sosman's paper in the *Journal of Geology*, 1916, do not find confirmation in the area above described.

Reviews

Kaolin of Indiana. By W. N. Logan, State Geologist. Indiana State Dept. of Conservation, Bull. No. 6, 1920. Pp. 131, pls. 43, maps (colored) 7.

Beds of kaolin occur at several horizons at or near the top of the Mississippian formation in several counties in southwestern Indiana. One important horizon is at the contact between a Chester shale (below) and a Pottsville sandstone (above). All the beds are beneath a sandstone and above a shale. There has been only a slight commercial development of the deposits to date, in spite of the presence of large quantities of high-grade white clays. The report discusses (1) the physical and chemical properties of Indiana kaolin; (2) its geological conditions of occurrence; (3) its origin; and (4) its uses. It also gives (5) its geographic distribution by counties.

Dr. Logan's study of the origin of Indiana kaolin has disproved earlier explanations. Laboratory experiments and microscopic examination have shown that this kaolin is due to biochemical action, an origin not before suspected. It was found that under proper conditions in the laboratory, sulphur bacteria secrete kaolin. In nature, sulphur bacteria obtain sulphur from the iron pyrite in the shale. The sulphuric acid which is formed, attacks the aluminum in the shale. The resulting compound reacts with the quartz of the sandstone, and the sulphur is replaced by silica, producing kaolin.

As kaolin in southern Indiana is being actively formed today by sulphur bacteria where the average annual temperature is 50° F., it is inferred that the kaolin deposits of the Tuscaloosa, Wilcox, and Lafayette formation of southern states were formed under similar temperatures. During the glacial epochs, some such average temperature doubtless occurred in the Gulf states.

S. S. V.

Recent Publications

—American Journal of Science, The. [Fourth Series, Vol. XLVII (1919), May. New Haven, Conn., 1919.]

—Ashley, G. H. The Abram Creek–Stony River Coal Field, Northeastern West Virginia. [U.S. Geological Survey, Bulletin 711-F. Washington, 1920.]

—Bassler, R. S. The Cambrian and Ordovician Deposits of Maryland. [Maryland Geological Survey Report. Baltimore, 1919.]

—Berry, E. W. Upper Cretaceous Floras of the Eastern Gulf Region in Tennessee, Mississippi, Alabama, and Georgia. [U.S. Geological Survey, Professional Paper 112. Washington, 1919.]

—Buchanan, J. Y. Accounts Rendered of Work Done and Things Seen. [Cambridge: University Press, 1919.]

—Buckman, S. S. Type Ammonites. (The illustrations from photographs mainly by J. W. Tutcher.) Part XX. Pp. 7, 8; 14 plates. [William Wesley & Son, 28 Essex Street, Strand. London, U.C. 2, 1919.]

—Burchard, E. F. Fluorspar and Crysolite in 1918. [U.S. Geological Survey, Mineral Resources of the United States, 1918. Part II, Sec. 14, pp. 317–29. Washington, 1919.]

—Cady, G. H. Geology and Mineral Resources of the Hennepin and La Salle Quadrangles. [Illinois Geological Survey Bulletin No. 37. Work in Co-operation with the U.S. Geological Survey. Urbana, 1919.]

—Canada Department of Mines, Annual Report on the Mineral Production of Canada during the Calendar Year 1918. [Ottawa, 1919.]

—Canada Department of Mines, Geological Survey. Summary Report, 1918, Part A. [Ottawa, 1919.]

—Chapman, F. Descriptions and Revisions of the Cretaceous and Tertiary Fish-Remains of New Zealand. New Zealand Department of Mines, Geological Survey Branch. [Palaeontological Bulletin No. 7. Wellington, 1918.]

—Clark, W. B., Mathews, E. B., and Berry, E. W. [Maryland Geological Survey Reports, Vol. 10. Baltimore, 1918.]

—Clarke, F. W. The Data of Geochemistry (4th edition). [U.S. Geological Survey, Bulletin 695. Washington, 1920.]

—Collier, A. J. Gas in the Big Sand Draw Anticline, Fremont County, Wyoming. [U.S. Geological Survey, Bulletin 711-E. Washington, 1920.]

———. Oil in the Warm Springs and Hamilton Domes, Near Thermopolis, Wyoming. [U.S. Geological Survey, Bulletin 711-D. Washington, 1920.]

—COOKE, H. C. Gabbros of East Sooke and Rocky Point. [Canada Department of Mines, No. 1762, Geological Survey. Museum Bulletin No. 30. Geological Series, No. 37. Ottawa, 1919.]

—DALL, W. H. Pliocene and Pleistocene Fossils from the Arctic Coast of Alaska and the Auriferous Beaches of Nome, Norton Sound, Alaska. [U.S. Geological Survey, Professional Paper 125-C. Washington, 1920.]

—DARTON, N. H. Geologic Atlas of the United States. Newell Folio, South Dakota. [U.S. Geological Survey, Folio No. 209. Washington, 1919.]

—DUNBAR, C. O. Stratigraphy and Correlation of the Devonian of Western Tennessee. [State Geological Survey of Tennessee, Bulletin 21. Nashville, 1919.]

—DUNLAP, H. L. The Carbonization of Missouri Cannel Coals. [School of Mines and Metallurgy, University of Missouri, Vol. V, No. 1 (Technical Series). Rolla, 1919.]

—DUNLOP, J. P., AND BUTLER, B. S. Silver, Copper, Lead, and Zinc in the Central States in 1918. Mines Report. [U.S. Geological Survey. Mineral Resources of the United States, 1918, Part I, Sec. 5. Washington, 1919.]

—EAKIN, H. M. The Porcupine Gold Placer District, Alaska. [U.S. Geological Survey, Bulletin 699. Washington, 1919.]

—FAY, A. H. Accidents at Metallurgical Works in the United States, during the Calendar Year 1918. [U.S. Bur. of Mines, Tech. Paper 256. Washington, 1920.]

———. A Glossary of the Mining and Mineral Industry. [U.S. Bur. of Mines, Bulletin 95. Washington, 1920.]

—FELDTMANN, F. R. The Manganese Deposits of Bulong, North-East Coolgardie Goldfield. With Notes on the Preparation and Uses of Magnesite. [Western Australia Geological Survey, Bulletin No. 82. Perth, 1919.]

—FERGUSON, H. G. Antimony in 1918. [U.S. Geological Survey, Mineral Resources of the United States, 1918, Part I, Sec. 4. Washington, 1919.]

———. Graphite in 1918. [U.S. Geological Survey, Mineral Resources of the United States, 1918, Part II, Sec. 10. Washington, 1919.]

—GEE, L. C. E. (Compiler). Mining Review for the Half-Year Ended June 30, 1919. No. 30. [South Australia Department of Mines. Adelaide, 1919.]

—GRAY, G. A. Gazetteer of Streams of Texas. [U.S. Geological Survey, Water-Supply Paper 448. Washington, 1919.]

—GROVER, N. C. Surface Water Supply of the United States, 1917. Part VII. Lower Mississippi River Basin. [U.S. Geological Survey, Water-Supply Paper 457. Washington, 1919.]

———. Surface Water Supply of the United States, 1916. Part IX. Colorado River Basin. [U.S. Geological Survey, Water-Supply Paper 439. (Prepared in co-operation with the states of Arizona, Nevada, Utah, and Wyoming.) Washington, 1919.]